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Energy Storage Systems Program Report for FY96

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Prepared by
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Energy Storage Systems Program Report for FY96

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Abstract

Sandia National Laboratories, New Mexico, conducts the Energy Storage Systems Program, which is sponsored by the U.S. Department of Energy's Office of Utility Technologies. The goal of this program is to assist industry in developing cost-effective energy storage systems as a resource option by 2000. Sandia is responsible for the engineering analyses, contracted development, and testing of energy storage systems for stationary applications. This report details the technical achievements realized during fiscal year 1996.

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Acronyms and Abbreviations

ABESS	Advanced Battery Energy Storage System
ACBC	AC Battery Corporation
ACE	area control error
ACU	Adaptive Control Unit
ALABC	Advanced Lead-Acid Battery Consortium
ALO	Albuquerque Operations Office
APS	Arizona Public Service Company
APT	Alternative Power Technologies
ASU	Arizona State University
BES	battery energy storage
BESS	battery energy storage system
BEWAG	Berlin Power and Light
CEC	California Energy Commission
CPD	constant-power discharge
CRE	El Camino Real Engineering
DA	Distribution Automation
DOD	depth of discharge
DOE	Department of Energy
DSM	demand-side management
ECP	Electricity Capacity Planning
EMM	electric market module
EPRI	Electric Power Research Institute
ESA	Energy Storage Association
ESD	electronic sensor device
ESS	Energy Storage System
FES	flywheel energy storage
FIM	factory-integrated modular
FIMS	factory-integrated modular storage
FSEC	Florida Solar Energy Center
GE	General Electric
GNB	GNB Technologies, Inc.
HELCO	Hawaii Electric Light Company
HPPCS	Hybrid Power Processor and Control System
IEEE	Institute of Electrical and Electronics Engineers
ILZRO	International Lead Zinc Research Organization, Inc.
IOUs	investor-owned utilities
IPALCO	Idaho Power & Light Co.
IPP	independent power producer

KCPL	Kansas City Power and Light Co.
LANL	Los Alamos National Laboratory
LDSM	Load and Demand-Side Management
LVD	low-voltage disconnect
MDL	Microelectronics Development Laboratory
MGTF	Modular Generation Test Facility
MOU	memorandum of understanding
NEMS	National Energy Modeling System
NERC	North American Electric Reliability Council
NEST	National Energy Storage Test
NMSU	New Mexico State University
NRECA	National Rural Electric Cooperative Association
NSP	Northern States Power
OC	open circuit
O&M	operations and maintenance
PC	personal computer
PCP	power control pair
PCS	power conditioning system
PEPCO	Potomac Electric Power Co.
PG&E	Pacific Gas & Electric
PLC	programmable logic controller
PNM	Public Service Company of New Mexico
PREPA	Puerto Rico Electric Power Authority
PV	photovoltaic
PVDF	polyvinylidene difluoride
R&D	research and development
RFM	Renewable Fuels Module
RFP	request for proposal
RFQ	request for quotation
RMSEL	Robotics Manufacturing Science and Engineering Laboratory
RT	recharge time
SCE	Southern California Edison
SDG&E	San Diego Gas & Electric
SI	Superconductivity, Inc.
SLI	starting, lighting, and ignition
SMES	superconducting magnetic energy storage
SMUD	Sacramento Municipal Utility District
SNL	Sandia National Laboratories
SOC	state of charge
SOH	state of health

SOW	statement of work
SPI	Silent Power, Inc.
SPL	Silent Power, Ltd.
SR	spinning reserve
SRP	Salt River Project
STAR	Solar Test and Research
T&D	transmission and distribution
TBESS	Transportable Battery Energy Storage System
TBS	Transportable Battery System
UBG	Utility Battery Group
UBS	Utility Battery Storage
UES	utility energy storage
UMR	University of Missouri–Rolla
UPS	uninterruptible power supply
UPVG	Utility Photovoltaic Group
VAR	volt-amp reactive
VRLA	valve-regulated lead-acid
ZBB	ZBB Technologies, Inc.

1. Executive Summary

Introduction

The U.S. electric utility industry is undergoing revolutionary change as a result of (1) impending deregulation and competition, (2) limitations on installing new conventional generation and transmission and distribution (T&D) equipment, and (3) greatly reduced resources for research and development (R&D). The United States Department of Energy (DOE), through the Energy Storage Systems (ESS) Program, continues to work cooperatively with the utility industry and the manufacturing sector to develop energy storage systems that will play a vital role during and after this transition period. In doing so, the ESS Program is furthering the goals of the DOE by developing technology that can be used by industry to (1) strengthen the nation's energy security in terms of electricity supply, (2) reduce the environmental impact of electricity generation, transmission, and distribution, and (3) increase the global economic competitiveness of U.S. industry with more reliable, higher quality, and cheaper electricity.

Like the utility industry, the ESS Program itself is undergoing changes. During the first quarter of FY96, the program restructured its previous five program elements into four, was renamed ESS, and redefined the program focus to include the full range of energy storage products. The ESS Program is conducting focused research and development, leveraged by U.S. industry, to stimulate the widespread use of energy storage systems for renewable generation and other electric system applications. In response to the changing needs of industry and the status of developing technology, the program has expanded to include a portfolio of storage technologies such as advanced batteries, flywheels, and superconducting magnetic energy storage (SMES) and has the goal of developing new energy storage systems with superior performance and higher energy densities at competitive prices.

The ESS Program balances the research and development of promising new technologies and equipment with focused analytical and educational tasks. The primary emphasis of ESS hardware development projects in FY96 was on the development of the Transportable Battery Energy Storage System (TBESS) and on the continuation of utility field experiments such as the GNB Technologies, Inc. (GNB) Vernon and Metlakatla Indian Community storage projects. Program initiatives in FY96 included the Advanced Battery System Development project and the mid-voltage storage system project. The FY96 program plan included a broad spectrum of landmark analytical activities such as estimating the market for battery energy storage (BES) in utility applications.

The ESS Program consists of four interrelated elements:

- Analysis
  - System Studies
  - Feasibility Studies
  - Opportunities Analysis
- Component Research and Development
  - Zinc/Bromine Battery Technology Development
  - Technology Evaluation/Applied Research at Sandia National Laboratories (SNL)
  - Valve-Regulated Lead-Acid (VRLA) Battery Reliability Improvement
- Integration and Implementation
  - Factory-Integrated Modular Storage (FIMS) Development
  - System Field Evaluation
- Information Exchange
  - Energy Storage Association (ESA)
  - Executive Briefings

This report summarizes each element's projects and tasks and describes the progress made on the projects in FY96.

Current analysis studies, which focus on quantification of application benefits, have allowed utilities to define the usefulness of storage and to make informed decisions regarding its suitability to their applications. Widespread acceptance of this technology by the utility industry will eventually make it possible for utility planners to routinely include energy storage in their planning scenarios.

Work in the Component Research and Development element focuses on improving the subsystems that make up energy storage systems: improvements are developed and evaluated in the primary components of the energy storage system, including the storage device (e.g., the battery) and the electrical equipment (power conversion and control). The ESS Program is developing storage components that cost less, have higher performance, and are better integrated with other parts of the system than those currently available.

Activities in the Integration and Implementation element involve pursuing a strategy that will reduce inefficient, one-of-a-kind system engineering historically required when an energy storage system is designed and built. A "modular" system approach has been adopted as the preferred method to achieve system flexibility and the lowest possible cost. The major subsystem components are designed as separate modules so that integration can occur either at the factory or the utility site. From a cost perspective, the modular approach permits more efficient engineering, design, and manufacturing processes. Performance and service-life qualification of hardware incorporating prototype designs is also performed. This activity involves the detailed characterization of performance, maintenance requirements, and reliability (service life) of integrated systems at relevant utility sites. The qualification of hardware incorporating prototype designs and associated manufacturing methods represents the final step of engineering development.

Work in the Information Exchange element concentrates on focused communication to promote interest in energy storage and to provide forums in which ideas are shared, information is exchanged, and cooperative projects are initiated. Between March and September of 1996, ESS Program management visited 15 organizations. The selected organizations all have technologies or business goals that may play a significant role in the eventual adoption of energy storage systems into the electric utility industry.

Highlights

Overview

Many projects initiated late in FY95 and during FY96 have been advanced significantly. A contract was placed with Frost & Sullivan to perform a market feasibility study that will provide a preliminary estimate of the market for BES in certain utility applications over the next 15 years. The first PQ2000 system has undergone a successful shakedown test and will now enter a comprehensive field test program. The final VRLA deliverable from GNB was placed in service, and field testing has begun. ESS Program staff completed the Executive Briefing presentation package and held 15 meetings with utility executives.

This year's Soltech Conference, held in Palm Springs, California, was the first to bring together representatives from both the electric utility industry and the solar energy companies. The program's presence at the conference emphasized the benefits to be gained by including storage in renewable energy projects.

Analysis

Quantification of Utility Cost Savings from Using Batteries—University of Missouri–Rolla

The University of Missouri–Rolla (UMR) is continuing to use the DYNASTORE computer program to calculate utility operating cost savings that can be realized with BES. Analysis of a grid-connected utility system at Kansas City Power & Light Co. (KCPL) has been completed for three battery applications: load leveling, spinning reserve, and frequency regulation. Frequency regulation provided the greatest predicted operating cost savings in this case, amounting to about $4M in 1996 for a 100-MW battery energy storage system (BESS). The revised final report for the KCPL study was submitted to SNL at the end of June.

Mid-Voltage Power Quality Device Project

SNL has been working with the Public Service Company of New Mexico (PNM), Los Alamos National Laboratory (LANL), and El Camino Real Engineering (CRE) to develop a storage system that can solve power quality problems at the substation level, i.e., 15 kV. SNL has proposed testing the first-of-its-kind system at Substation 41 (at SNL) because industry members are reluctant to test and prove the technology at their production facilities.

Market Feasibility Study

To better orient BES development and commercialization efforts to the needs of the marketplace, SNL began developing the request for proposal (RFP) for a market study in 1995. Frost & Sullivan was retained in May 1996 to conduct the study. Frost & Sullivan began by identifying a pool of contacts that would receive a questionnaire and participate in a survey. The pool included contacts from utilities, including investor-owned utilities (IOUs), independent power producers (IPPs), and cooperatives. Frost & Sullivan also identified contacts in the battery system supplier industry, consultants, and regulatory bodies such as state regulatory commissions and other similar agencies.

Conclusions drawn from the study indicate that BES and SMES are more competitive for power quality applications for two primary reasons. First, the power quality problems experienced by industry are very similar in nature; hence, a uniform product line can be developed and marketed, achieving economies of scale. Second, because of the large economic losses caused by power supply perturbations, industries are willing to invest substantial amounts in equipment to shield them from these perturbations. The increasing sensitivity of customer machinery to these disturbances presents a growing market for protection systems. Cost projections indicate a 10-20% cost reduction for BES and a 30-40% cost reduction for SMES systems in this application. Cost reductions through technology improvement and volume manufacturing are essential for the competitiveness of all the technologies (SMES, FES and BES) and system components addressed in the study. More of the survey findings can be found in Section 2 of this report.

Cost Analysis of Energy Storage Systems

Early in FY96, SNL placed a contract with Sentech, Inc., to conduct a cost analysis of energy storage systems for electric utility applications. The study estimated the current cost breakdown of energy storage systems using three of the most promising storage technologies: batteries, advanced flywheel energy storage (FES), and SMES. After extensive discussions with system and component suppliers, project engineers were able to identify the potential for cost reductions in key components. Preliminary results verify that energy systems potentially have widespread applications within the electric utility industry. The three technologies analyzed each meet some of the performance requirements of the 13 utility applications identified in *Battery Energy Storage for Utility Applications: Phase I - Opportunities Analysis*, a report on a study conducted by SNL. These preliminary results, along with tables summarizing the cost of projects and storage system products, are presented in Section 2 of this document. The complete study will be published as a SAND report early in FY97. Confidential and proprietary information will be protected and will not be disclosed in the final report.

PV/Battery Charge Controller Market and Applications Survey

The contract to conduct a Photovoltaic (PV)/Battery and Charge Controller market and application survey was placed with Arizona State University (ASU) in June of 1995. This survey provided (1) quantification and characterization of batteries and charge controllers used in PV systems; (2) characterization of the operating environment in which batteries and charge controllers are used; and (3) feedback from PV system integrators, battery manufacturers, and charge controller manufacturers defining what information each needs to optimize PV energy storage systems.

Preliminary results from survey respondents identified areas of focus by each of the three industries (PV system integrators, battery manufacturers, and charge controller manufacturers) in which they would like SNL's assistance. The high-priority areas identified were (1) assisting in the development of application guides or notes, (2) assisting in the characterization of batteries for PV data sheet values, (3) providing technical liaison between the PV and battery industries, and (4) performing surveys to define the market.

Under the contract, results from the survey were scheduled for publication by June 30, 1996. However, an inordinate amount of the time was required to eliminate conflicts in data reported, which resulted in a contract extension to December 31, 1996. The final report will be published and distributed as a SAND document during the first quarter of FY97.

Incorporation of BES into the National Energy Modeling System

In July 1996, Sentech, Inc., completed a study addressing how BES can be incorporated into the Electric Market Module (EMM) of the National Energy Modeling System (NEMS). The purpose of the study was to assess the feasibility of, and to make recommendations for, developing methodologies to incorporate storage in stand-alone dispatchable units. Also, storage with renewable generation as an integrated unit was modeled.

The study concluded that three possible avenues exist for including storage technologies within the EMM. However, the study recommended that analytical work be carried out only on integrating storage with renewable technologies and that a thorough assessment be made of the potential benefits storage can bring to the renewable generation technologies.

Component Research and Development

Zinc/Bromine Battery Development

The zinc/bromine battery development project is being completed through an in-kind cost-sharing contract with ZBB Technologies, Inc. (ZBB). ZBB recently completed a move into a 13,000-sq.-ft facility in Wauwatosa, Wisconsin. Facilities were prepared at this installation for the manufacturing and testing of zinc/bromine batteries.

Unexplained shutdowns of the inverter were identified and a new controller board is scheduled to be installed in December 1998. Safety prequalification testing was completed. Optimization of battery performance will commence once the new controller board is installed.

Methods were developed to electrically isolate the voltage so that the programmable logic controllers (PLCs) would be able to consistently read battery voltages without being affected by noise from the power conditioning system (PCS). Also, calibration of the voltage and current sensors for the modules and the final logic and data acquisition software were completed.

The electronics and software to run the battery were tested. Testing was initiated on a three-battery configuration. These stacks were some of the first few built and did not meet quality specifications. However, they did perform very consistently during the 18 cycles for which they were tested, with the final cycle giving coulombic efficiency of 79.6%, voltaic efficiency of 87.7%, and energy efficiency of 69.9%.

Minor changes were made in the software and ladder logic to enable the battery to run unmanned cycles. Strip resistors have been added to the system to allow unmanned stripping of the battery. Once the new controller board is installed in December 1998 (with new software), a major portion of the stripping function will be performed by the PCS.

PV Battery Testing

PV battery cycle-life tests are being conducted on the GNB 12-5000X 12-V batteries. A dozen batteries were received in April 1996; two of the twelve batteries were put on test immediately. The remainder of the batteries were left on the shelf in a fully charged condition. After 6 mo it was discovered that the batteries had lost up to 30% of their capacity due to self-discharge effects.

VRLA Evaluation at SNL

ABSOLYTE II and IIP Testing

Testing of the GNB ABSOLYTE II 18-V battery continued during FY96. This battery was subjected to several series of constant-current discharge tests. These were done to characterize the battery at the C/2, C/8, and C/20 rates to 100% depth of discharge (DOD) and also to compare the performance of the ABSOLYTE II design with that of the enhanced ABSOLYTE IIP design at the same discharge rates. During the third quarter, a study was initiated to determine the effect on discharge capacity of float charging at specific constant voltage levels. The purpose of this study was to provide guidance to New Mexico State University (NMSU) in the setup of renewable systems for the U.S. Coast Guard, which uses ABSOLYTE technologies for energy storage.

VRLA Reliability Improvement

VRLA battery reliability has been questioned recently, particularly by users of standby power systems. Because SNL believes that this battery technology offers significant advantages for utility and renewable energy applications, a VRLA reliability improvement project is being formulated. Yuasa-Exide, Inc., was visited to obtain a manufacturer's perspective on VRLA reliability issues. VRLA failure modes were discussed, and PCS requirements were identified as an area that needs to be standardized. Interest was also expressed in obtaining independent test data on utility battery products. Possible areas for future collaboration are being defined. Internal discussions are continuing on ways to structure a general reliability study that would attract strong support from the VRLA battery manufacturing community. No conclusions have been reached at this point about how this effort should be organized, although teaming with other organizations that sponsor research in the VRLA battery field may be a worthwhile approach.

Sodium/Sulfur Applied Research at SNL

SNL is concluding an effort to develop thermal fuses as a safety device for sodium/sulfur batteries. Fusing tests have been carried out on several different prototype cast metal fuses that contain a variety of gap widths between their electrical leads. The objective was to evaluate several alloy formulations that melt in the desired temperature range to determine which drop cleanly from the fuse at the smallest gap width. It was found that all of the candidate materials performed better when the fuses were tested in an inert atmosphere to prevent the metals from oxidizing. Increasing the gap width between the leads from 5 mm to 10 mm also helped most of the trial fuses to open more reproducibly in air. The most promising fuse material has a melting point of approximately 460°C. Data reduction is complete and work on a summary report of all of the fuse studies has begun.

Integration and Implementation

Factory-Integrated Modular Systems (FIMS)

AC Battery Development Contract Wrap-Up

A draft final report on the PM250, *Final Report on the Development of a 250-kW Modular, Factory-Assembled Battery Energy Storage System*, was received from Omnion Power Engineering Corporation. Following review and markup, the PM250 final report will be published as a SAND report for distribution early in FY97. The *PM250 Prototype Production Cost Estimate Report* was also received in late FY96, and will be incorporated into the development report.

Transportable Battery Energy Storage System (TBESS)

On August 1, 1996, negotiations were completed and the TBESS contract was awarded to AC Battery Corporation (ACBC) in East Troy, Wisconsin. This project is part of a collaborative activity known as the Transportable Battery System (TBS) Program, which is an initiative of DOE and the Electric Power Research Institute (EPRI). A contract was to be placed for the design, fabrication, and testing of a utility-scale transportable battery system to be evaluated at multiple sites in partnership with a selected utility. SNL collaborated with EPRI on the development of the statement of work (SOW) for this project, and a similar project was initiated by EPRI. An RFP was issued by SNL in late FY95. The goal of the project was to further the deployment and evaluation of prototype battery systems built with commercially available and advanced components in typical utility operating environments.

Advanced Battery Energy Storage System (ABESS)

The request for quotation (RFQ) for the Advanced Battery Energy Storage System (ABESS) project was released by SNL in mid-January of FY96. The deadline for quotes was March 1996. Several proposals were received; however, additional information was needed in order to adequately evaluate the proposals. A letter requesting additional, specific information from the proposers was sent out and the deadline for submission extended to July 1996.

Analysis of the proposals resulted in two companies receiving high ratings. Currently negotiations are under way with both companies to see if a contract can be placed with one or both of them.

System Field Evaluation

AC Battery PM250 Prototype Renovation Project with AC Battery Corporation

During FY96, the ACBC prototype PM250 container underwent complete refurbishment and checkout at the AC Battery Corporation (ACBC) facilities in East Troy, Wisconsin. Initial evaluation of the container at ACBC indicated that multiple problems had occurred during the long period that the container spent sitting idle on the Modular Generation Test Facility (MGTF) test pad while the modules were being retrofitted with new batteries at Delphi Energy Systems. During the third quarter of FY96, the eight PM250 modules, complete with new AES 2010 batteries, were thoroughly checked out while they were at Delphi Energy Systems in Indianapolis, Indiana. The modules were shipped to ACBC during the fourth quarter of FY96. The systematic checkout performed by the ACBC engineers and technicians resulted in the elimination of many problems. Startup is expected in early October when all of the modules are mated with the container for full-power testing.

Field Test of PQ2000

The first PQ2000, which was designed and fabricated under a program jointly sponsored by Pacific Gas & Electric (PG&E), ACBC, Omnion Power Engineering Corporation, the state of Wisconsin, and the U.S. DOE, was shipped from ACBC to the PG&E MGTF in mid-April of FY96. Following a successful shakedown test, the PQ2000 entered a comprehensive field test program.

Field Test of Final VRLA Deliverable

An approximately 250-kW/500-kWh VRLA battery deliverable was furnished by GNB for a field test at the conclusion of its development program. The site selected for this 4-yr test was the GNB lead recycling center in Vernon, California, where a larger battery was being assembled to support critical plant loads during power outages. The ESS Program deliverable was incorporated into this larger 3.5-MW system and makes up about 10% of the battery cells.

A successful test was carried out in November 1995 that demonstrated the ability of the BESS to take over from the local electric utility, support the recycling plant load, and then synchronize with the utility feeder to return the load to the utility. Other data were collected during these trials to verify the plant load shed algorithm, to determine plant harmonics and the response time of the battery system, and to verify various BESS operator and display panels, battery state-of-charge (SOC) algorithms, and data screens.

PV/Hybrid Evaluation Project

Following a year-long search for an appropriate utility test site for the Hybrid Power Processor and Control System (HPPCS), the Arizona Public Service Company (APS) has agreed to sponsor a 1- to 3-yr test program for the HPPCS at the APS Solar Test and Research (STAR) Center. The HPPCS was developed by Omnion Power Engineering under a program sponsored jointly by SNL's Energy Storage Systems Department and its PV System Applications Department. Also included in the APS field test program will be the evaluation of a fuzzy-logic-based Adaptive Control Unit (ACU) developed by Raydec under a contract administered by the PV System Applications Department.

Information Exchange

Work in the Information Exchange element concentrates on focused communication to promote interest in energy storage and to provide forums in which ideas are shared, information is exchanged, and cooperative projects are initiated. Between March and September of 1996, the DOE Program team (the DOE ESS Program Manager, the ESS Program Manager at SNL, and an industry expert) met with representatives of diverse divisions of various organizations throughout the U.S. Altogether, 15 meetings were held.

Many companies are very interested in power quality as an application for storage in the next few years. Because of drastically reduced R&D budgets, many companies were interested in obtaining assistance from the DOE or from other organizations that deal in new ways to approach these projects. Several companies expressed interest in co-funding research projects with the ESS Program, with the intent of collaborating on possible projects in FY97.

2. Analysis

Introduction

The purpose of the Analysis element is to identify high-value benefits of energy storage in a wide variety of utility applications. The activities in this element have enabled utilities to quantify the usefulness of battery storage and to make informed decisions regarding its suitability to their applications. Widespread acceptance of this technology by the utility industry will eventually make it possible for utility planners to routinely include energy storage in their planning scenarios. Such acceptance is necessary for the eventual commercialization of this technology. There are three subelements in the Analysis program element: (1) system studies, (2) feasibility studies, and (3) opportunities analysis.

The "system study" is an initial screening study performed in collaboration with a host utility to identify and evaluate the potential benefits of energy storage to that utility. This screening-level study establishes a rough estimate of the benefit-to-cost ratio of storage using a limited examination of utility-specific operating and financial data as a basis.

A follow-on "feasibility study" firmly establishes the quantitative value of energy storage to a higher level of confidence by examining detailed forecasts of utility operating costs and other operational parameters for the entire operational life of the storage system. A site-specific conceptual design is included in the feasibility study to determine the cost of the storage system needed to generate these benefits.

Using the findings of the system and feasibility studies, the "opportunities analysis" (1) estimates the benefits of battery storage on a national level by identifying the market size, specific applications, and timing of the market and (2) defines the application requirements at the system level and matches each battery technology with application requirements that fit the battery's characteristics.

The Analysis element is based on the findings and results of earlier Gateway and Opportunities Analysis studies. The current studies focus on a need for further quantification of application benefits and assessment of the penetration of battery storage systems into the utility market. The overall objective is to continue pursuing new information in all of these areas to advance the programmatic goals of the ESS Program. Most of the information from these studies is also valuable to the industrial partners of the ESS Program and supports their entry into the emerging commercial market. As such, these studies will be performed either with direct collaboration or with substantial input from one or more industrial partners.

System Studies

Quantification of Utility Cost Savings from Using Batteries – UMR

This task was activated during FY94 by placing a contract with UMR to use EPRI's DYNASTORE computer program to perform calculations of utility operating costs with and without BES on the system. Operating cost savings are one important component of the battery system cost/benefit picture, along with the system capital cost and other projected utility benefits. In this initial study, UMR calculated generating costs for a medium-sized utility system that was not interconnected with other utilities. The results of this work showed that significant production cost savings could be obtained by using a battery system for spinning reserve.

In FY95, a new contract was placed with UMR for a follow-on study to perform a similar operating cost analysis for a grid-connected utility system. KCPL, which was selected as the subject for this new study, is a typical Midwestern electric utility with many interconnections and a mix of generating plants. The approach was again to run a unit commitment program on energy storage units along with generating units and calculate operating costs with and without energy storage, so that savings could be quantified. In this case, a spreadsheet was programmed to add fixed costs to the fuel and other variable costs calculated by DYNASTORE. This was done to allow the utility to more easily check the calculated costs against their actual operating costs for a base case that did not include energy storage. These checks were completed toward the end of FY95 with the conclusion that the agreement was close enough to consider the model to be valid. Work therefore proceeded on estimating the operating cost savings from the load-leveling, spinning-reserve, and frequency regulation BES applications using DYNASTORE.

Status

Work on this project was completed during the third quarter. A draft final report of the results was submitted to SNL by UMR prior to a review meeting that was held on June 12, 1996. Changes to the final report were made by UMR in response to comments made at the review, and a revision was submitted before the end of June. The results in the revised final report are summarized below.

The BESS parameters used for this study are listed in Table 2-1. The same charge and discharge capacities were used; these ranged from 40 to 300 MW to include the spinning-reserve requirement. BESS energy capacity ranged from 1 to 8 hr in duration to cover the time width of most load peaks.

As in earlier analyses of isolated utility systems, annual operating cost savings were calculated for two different years, in this case 1995 and 1996. The BESS applications studied were spinning reserve, load leveling only, load leveling with spinning reserve, and frequency control. For all except the spinning-reserve application, the production cost savings were found to increase almost linearly for the range of BESS sizes considered.

The study demonstrated that a BESS can provide savings in operating costs for a typical Midwestern utility (summer-peaking). The following is a breakout of how each application performed:

1. For spinning reserve only, savings increased with MW capacity up to the spinning-reserve requirement of 6%, which is approximately 180 MW for the KCPL system. The savings then leveled off and decreased slightly as BESS capacity was increased to 300 MW (see Figure 2-1). It was assumed for this study, based on experience with other utility applications, that a BESS of 1-hr duration is sufficient for spinning reserve. It follows that a BESS duration of 4 or 8 hr affords no more savings than the 1-hr duration, i.e., the smaller-duration BESS provides more savings per dollar cost than do larger-duration (larger energy capacity) systems.

2. For load leveling only, the savings were not significant for a short-duration BESS of 1 hr or less; even if the BESS size is increased from 40 to 300 MW, the savings were not very large (Figures 2-2 and 2-3). Conversely, as BESS energy is increased from 1 hr to 8 hr in duration, savings do increase significantly, because the BESS is able to shave peaks of longer time duration; therefore, the BESS is committed to more peak-shaving time by the DYNASTORE unit commitment algorithm.

3. For load leveling with spinning reserve, the curves for savings are flatter than for load leveling only, with generally small increases in savings for longer durations (see Figure 2-4). A small-capacity BESS tends to be more valuable for spinning reserve, whereas a large-capacity BESS tends to be more valuable for load leveling. The saturation of spinning-reserve savings for a BESS size above 200 MW is consistent with the 6% spinning-reserve requirement (177 MW for a KCPL system peak of 2947 MW).

4. Of all the BESS applications, frequency regulation yields the greatest savings for this utility (Figure 2-5). The savings increase with increases in BESS MW size up to approximately 300 MW. For frequency regulation, a 1-hr BESS is adequate because of the North American Electric Reliability Council (NERC)

Table 2-1. BESS Parameters

Discharge Capacity	Variable: 40 MW-300 MW
Charge Capacity	Variable: 40 MW-300 MW
Variable O&M Cost	0$/MWh
Efficiency (AC-DC-AC)	75%
Energy Storage Duration	Variable: 1 - 8 hr

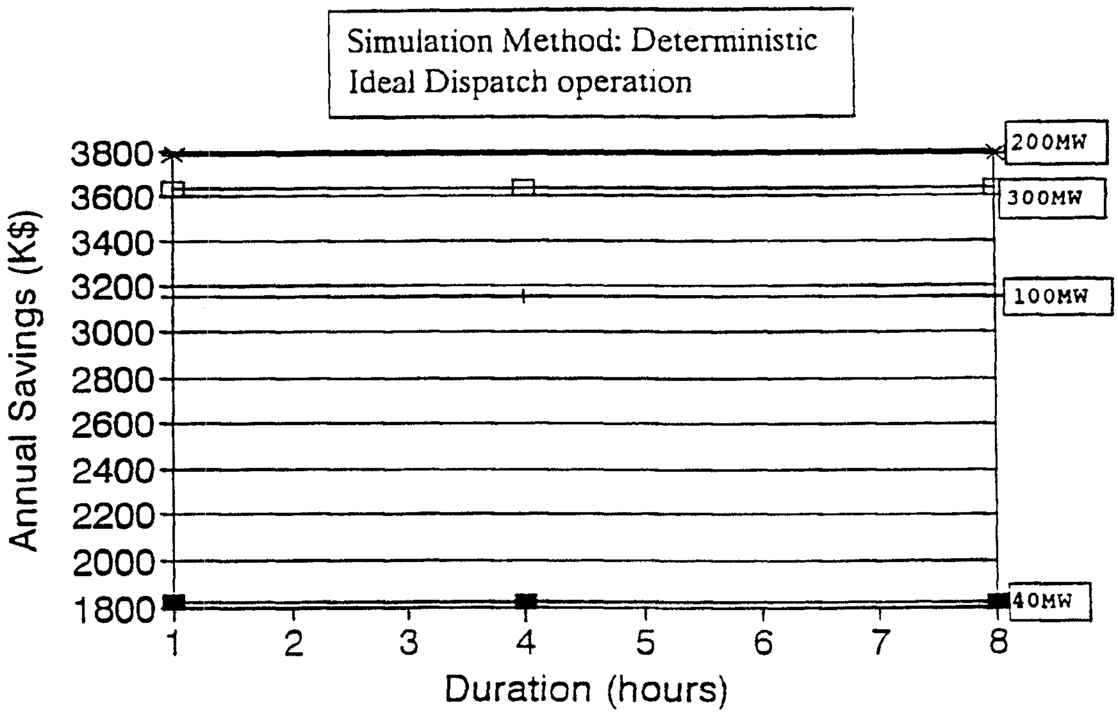


Figure 2-1. BESS Used for Spinning Reserve Only (1995).

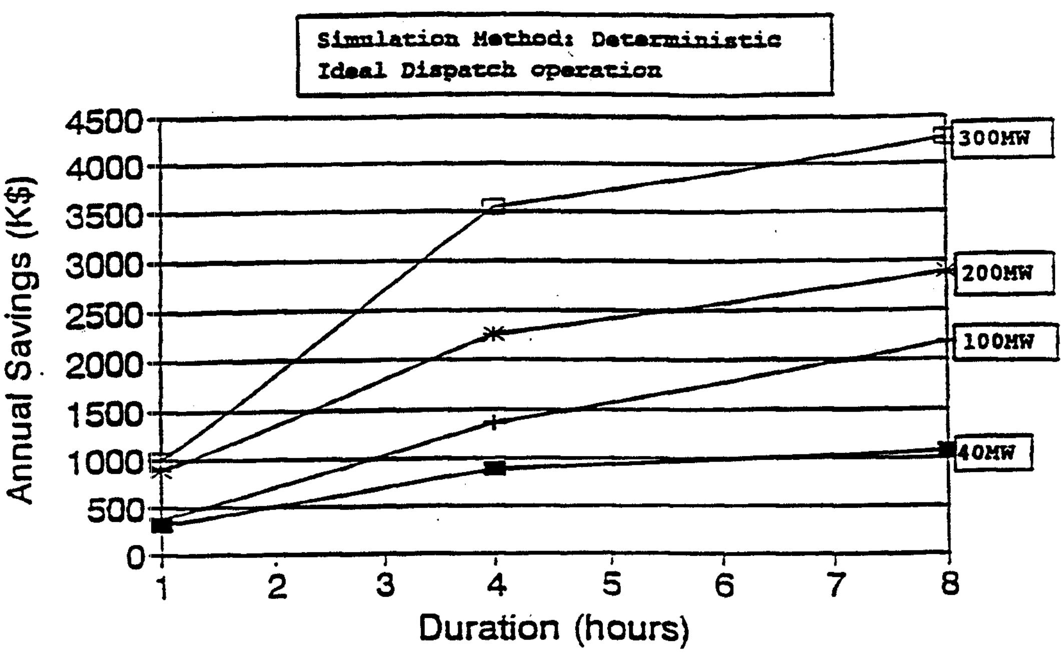


Figure 2-2. BESS Used for Load Leveling Only (1995).

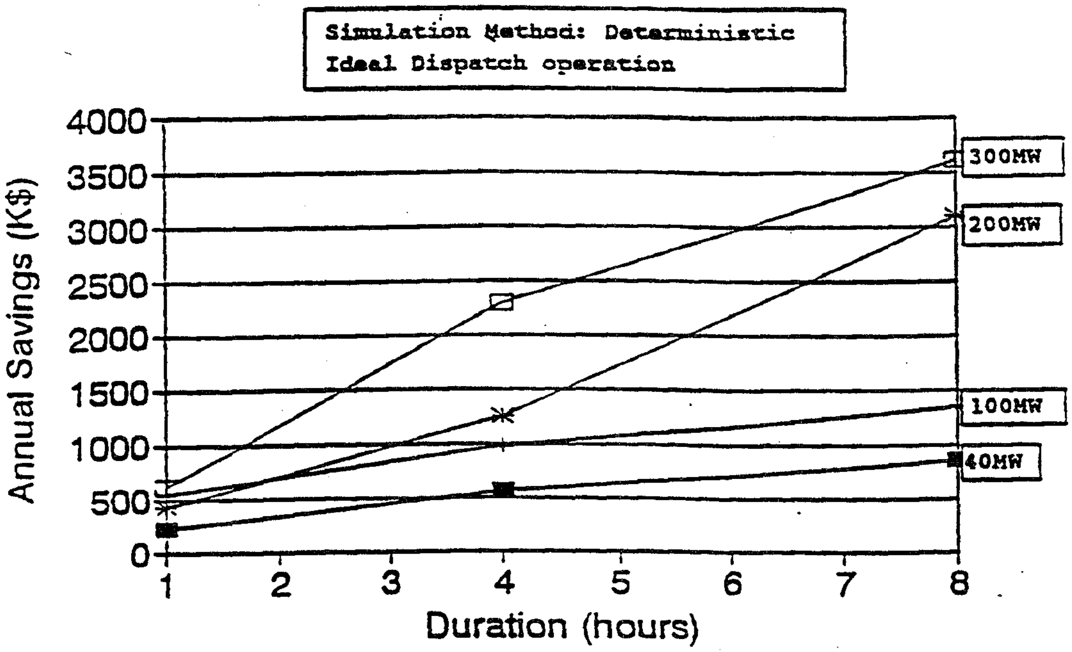


Figure 2-3. **BESS Used for Load Leveling Only (1996).**

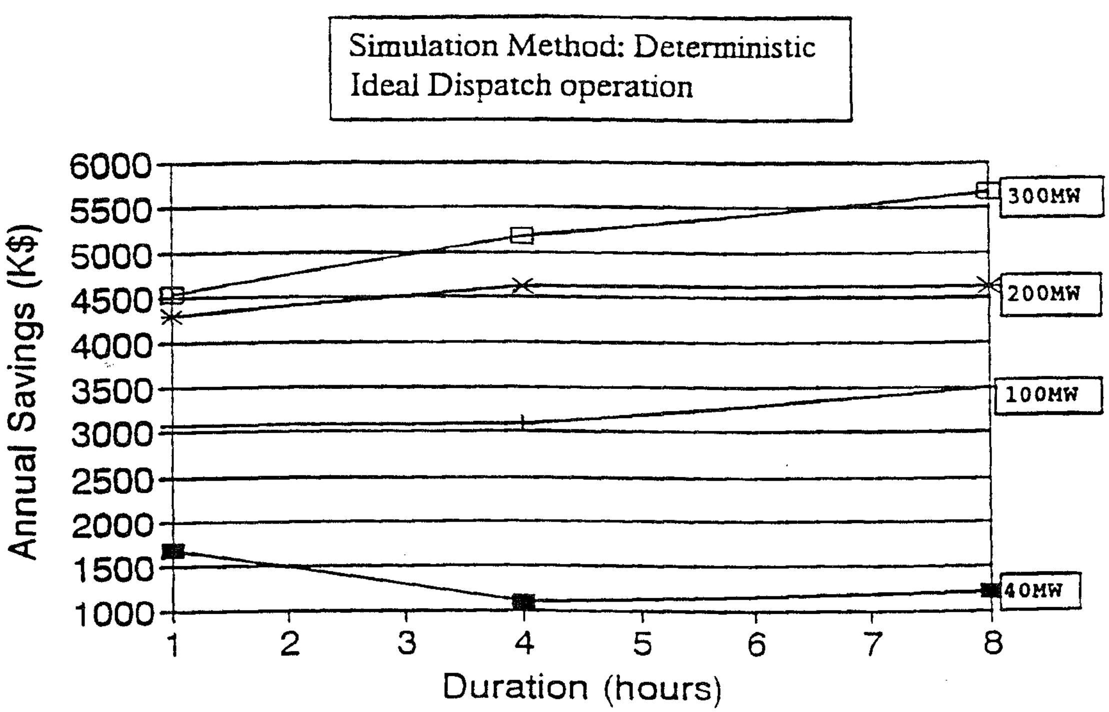


Figure 2-4. **BESS Used for Load Leveling, Including Spinning Reserve (1995).**

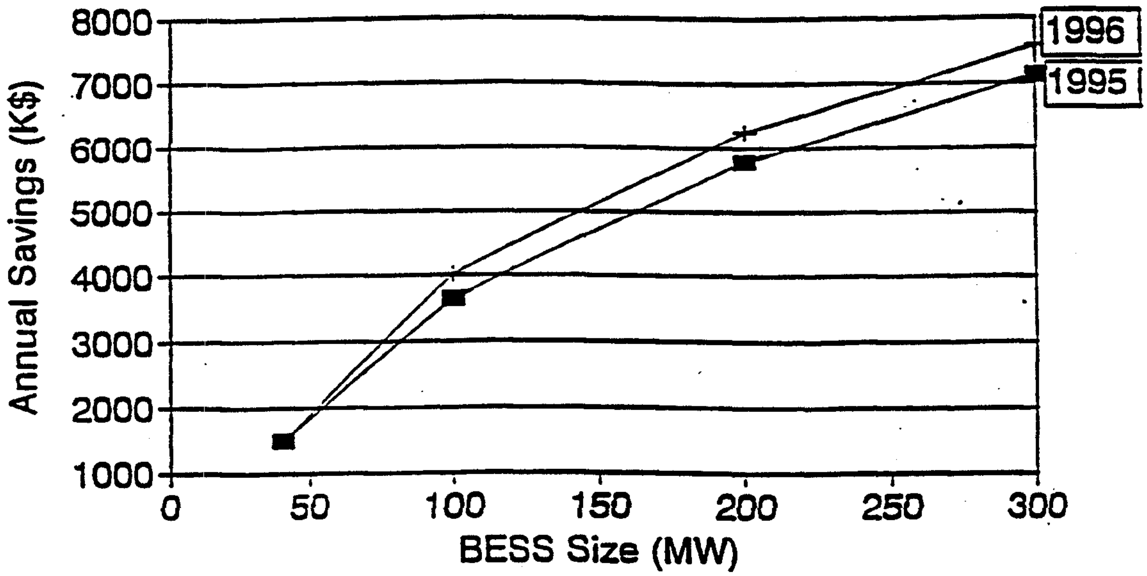


Figure 2-5. BESS Used for Load Frequency Control.

requirement that area control error (ACE) be controlled to zero every 10 min. Results show that the greatest savings are for the frequency regulation application, amounting to about $4M in 1996 for a 100-MW BESS.

Mid-Voltage Power Quality Device Project

The purpose of this project is to develop a power quality device capable of protecting large power-quality-sensitive facilities from the adverse effects of utility power system disturbances. Mid-voltage power quality devices are a means of preventing disturbances on the upstream utility grid or downstream feeders from affecting the bus voltage by isolating the bus from the disturbance. A Demonstration-Unit Siting Study was conducted in FY95 that identified Substation 41 at SNL as the ideal location for testing the device.

As part of the long-range vision for the ESS Program, the demonstration site for the mid-voltage power quality device has evolved into the concept of the National Energy Storage Test (NEST) Center. As envisioned, the mission of the NEST Center would be to evaluate the suitability of storage technologies including batteries, capacitors, and flywheels as energy sources for the mid-voltage power quality device concept.

Work in FY96 focused on incorporating the mid-voltage power quality device concept into the design of Substation 41 and on further conceptual development of the NEST Center.

The project team established the work program for 1996 using as a basis the following lessons learned from the project:

- There is a market need for a medium-voltage, utility-substation-level power quality device. Market demand, however, is dependent on a well-thought-out, well-publicized, and successful demonstration of the system.
- Market demand is also highly dependent on cost, and reducing cost is as important as successfully demonstrating the technology.
- Potential user industries, such as the semiconductor manufacturing industry, are unwilling to test a prototype device at their facilities.
- Finding funding and support from government and industry for a $17M demonstration project

to build a first-of-its-kind SMES-PAC™/mid-voltage power quality device is impossible given the economic realities of the day. This estimate was for a 20-MW device with a 40-to-50-MJ SMES.

These findings led the project team to focus on developing a proposal for a demonstration project that is meaningful yet supportable. It was determined that the following attributes represented a meaningful and supportable demonstration of the technology:

- The device must be demonstrated at a voltage (15-kV class) and power (10-12 MW) that make it unique from the products available on the market today. Although it was initially desirable to demonstrate something in the 20-MW class, by reducing the power to 10-12 MW the cost can be reduced while still maintaining a size larger than that of currently available products.
- The device should be applied on the utility side of a medium-voltage substation. This differentiates the device from the customer-based power quality products that are available in the marketplace today.
- The device should be demonstrated at a site that serves facilities that are sensitive to power quality problems and disturbances and emulates the power quality needs of high-tech industrial facilities.
- The total cost of the project should be on the order of $5-6 M (or less if possible) amortized over 2-3 yr. Although this cost ceiling was arrived at somewhat arbitrarily, it is a target that seems necessary given the funding considerations and cost requirements of the market.
- The project should be cost-shared by government and industry.
- The storage technology is not sacrosanct (i.e., it does not have to be SMES). It was determined that the project team would choose the most appropriate storage technology with primary consideration given to minimizing the cost and risk. Demonstrating a medium-voltage power quality device at a reasonable cost was more important to the project's success than that a particular storage technology be chosen.

The DOE has verbally approved the baseline change request for the construction of Substation 41 at SNL/NM. This substation is scheduled for completion in March 1998. An initial meeting with SNL Facilities personnel has been held. The purpose of the meeting was to explore the possibility of demonstrating the proposed power quality device on Substation 41. During that meeting, the following criteria were developed jointly by the power quality project team and facilities personnel:

- During startup of the device, only those facilities that have agreed to accept the risk (and potential benefit) of such a device should be fed from Substation 41. It was agreed that the power quality project team approach representatives from the Microelectronics Development Laboratory (MDL) and the Robotics Manufacturing Science and Engineering Laboratory (RMSEL) as potential user facilities.
- The system will need to be designed in such a way that the power quality device can be bypassed.
- Facilities retains the right to bypass the power quality device at any time and return the substation to "normal" operations in the event that they need the capacity to meet their load requirements.

The other significant development is that the project team members, LANL, PNM, CRE, and SNL, have identified at least one manufacturer who is interested in and appears capable of developing a medium-voltage, substation-level power quality device and demonstrating it at SNL. Initial discussions with this manufacturer also indicate that the project constraints outlined above (cost: $5-6 million; and schedule: installation to coincide with the completion of Substation 41 in March 1998) are not unreasonable. The project team's objective over the next several months will be to develop a specific project proposal for designing, building and testing a medium-voltage, utility-substation-level power quality device. Work will also continue on developing a plan for testing the device on Substation 41 at SNL.

Status

PNM has taken the lead role in exploring and evaluating potential collaborators and investors. PNM and CRE are also now reviewing the economic viability and commercialization potential of the mid-voltage power quality device concept. Indications at this point are that PNM will aggressively continue pursuing the project; PNM has asked SNL to step up its efforts in determining whether PNM will be chosen as the host site for the demonstration project and what its interests and role will be as a major stakeholder.

As a result of the increased interest by PNM, SNL has initiated upper-level discussions (Director and VP levels) with the major internal stakeholders that would be involved with the project and is now assessing their interest in and requirements for participation in the project. The internal stakeholders who have been contacted include representatives from Facilities, the MDL, and the RMSEL and the Vice President of the Energy and Environment sector. All preliminary indications are that SNL is willing to continue exploring the possibilities; SNL plans to formulate a special task team to quantify stakeholder issues and begin the negotiation process with PNM.

In parallel with these efforts, ESS personnel have initiated more detailed discussions with representatives from SNL Facilities about the requirements for integrating a Mid-Voltage Power Quality Device Facility into Substation 41. Facilities representatives are now reviewing the draft SOW submitted by ESS personnel.

Chugach and SMUD Feasibility Studies

Work on both the Chugach and Sacramento Municipal Utility District (SMUD) Feasibility Studies was completed in 1995. Most of the Chugach study is supported by EPRI through collaboration with Chugach and by ESS funding, which supports a smaller portion of the total work. The EPRI funding includes funds for evaluating the benefits and economics of BES systems as well as those of SMES. This work compares the costs and benefits of both technologies for the same applications. The results of the studies will be available only to the subscribing members of EPRI. The ESS funding is used to support only the battery storage portion, and the results for this portion will be publicly available. Consequently, the final report will be divided and issued in two separate volumes, each covering the respective scopes. Because of the narrow focus of the ESS funding, the report that will be delivered to the ESS Program will be a shortened version of the full EPRI report. However, in order to preserve continuity and coherence, there will be appropriate text to explain the link between the two efforts, and the results will be cross-referenced as much as possible. The intent is to make each report as self-contained as possible.

Status

Chugach issued a draft final report for review by both the ESS Program and EPRI staff. It is expected that the reviews will be completed in late 1996 and a final report for the ESS Program portion will be released in Spring 1997.

The SMUD report was completed and sent to SMUD in April 1995 for review and comment.

Market Feasibility Study

The Market Feasibility Study is based on the results of the Opportunities Analysis performed earlier. This study was designed specifically to quantify the expected energy storage penetration into the utility market. The Opportunities Analysis, which was completed during FY95, characterized the opportunities for batteries to provide electric utility energy storage (UES) options. The study indicated that the implementation of BES systems on both sides of the utility meter could result in benefits of $57 billion between 1995 and 2010 for U.S. utilities and the nation. However, the potential benefits described in this analysis are more than an order of magnitude greater than those that can be realized by the market as it exists today, thus raising the question of whether there is indeed a significant market for BES systems. A Market Feasibility Study was performed in FY96 to determine if enough potential markets exist to motivate BES businesses to make the investment necessary to develop viable products.

Status

Frost & Sullivan conducted the survey through respondents in several "pools" comprised of electricity providers, BESS vendors, regulators/consultants, and other technology advocates. The electricity provider pool broadly includes IOUs, IPPs, and cooperatives. About 65 contacts were identified and participated in this survey.

The perceptions of the present and future roles of BES differ significantly depending on the group or organization. The electricity provider's perspective can be best categorized as cautiously optimistic. On the whole, electricity providers see roles for BES, especially in distributed generation and power quality, but they expressed significant concerns about BES costs, life span, maintenance, and energy density.

Electricity providers expect to increase their use of BES in the future, but they would like to see the shortcomings of the technology addressed and believe this is necessary to make widespread deployment of BES possible. As a result of concerns about the technology's shortcomings, BES is not currently viewed as being competitive with most generation technologies. In particular, electricity providers expect combustion turbines to provide better functionality over time than BES. However, interest in fuel cells was high, and batteries received considerable support because of their modularity, responsiveness, and especially their environmental friendliness.

During the course of the survey, respondents were questioned four times on the potential applications for which they might use BES. Table 2-2 and Figure 2-6 illustrate some of the responses to this question and show that power quality and reliability were the most commonly cited applications for BES.

Currently, BES products in the marketplace are based on either flooded lead-acid or VRLA battery technologies. In the near future, through 2000, most BES suppliers do not expect to move to different battery technologies, although they expect to further refine their power conversion technologies.

Perceptions of BES technology also varied widely between those that felt that existing BES technology was adequate and those that felt it was inadequate. As expected, those that supported existing BES technology tended to be organizations that were not aggressively developing advanced batteries and power conditioning equipment. Most respondents agreed that further advances in power conditioning and utility connection equipment could be made.

Surveyed regulatory agencies and industry groups provided the other industry perspectives in this study. Input from both types of organizations provides important supporting information for the conclusions reached in this study.

The responses received from regulatory agencies indicate that they do not have an established position on BES. Regulatory agencies receive little information or feedback from utilities, BES suppliers, or other organizations and do not view BES as a major issue. When they do receive information, it is primarily about combustion turbine and renewable technologies. Regulators concluded that market-based solutions focusing on economic costs and benefits will likely prevail, and the prospects for regulatory agencies using their influence to champion BES deployment are minimal.

The other industry groups that Frost & Sullivan contacted during this study were various organizations with an interest in the electric power industry and the use of BES. Examples of such organizations are the National Rural Electric Cooperative Association (NRECA), the Environmental Defense Fund, and the National Association of Utility Regulatory Commissioners. These industry groups had more specific perceptions of BES than the regulatory agencies.

Many of the groups viewed BES as an important enabling technology to facilitate the use of renewable energy or to solve power quality and asset utilization issues. These groups tended to be more focused on BES and maintained personnel that attempted to keep track of developments in BES markets and technologies.

BES Market Opportunities and Forecasts

The responses from the 21 utilities were compiled and extrapolated to the U.S. industry as a whole. The extrapolation used a formula based on each utility's percentage share of industry output and capacity. A similar method was used to extrapolate the electricity end-user BES demand estimates that Frost & Sullivan made using the responses of contacted BES suppliers and consultants. These figures are presented with the electricity provider estimates (Tables 2-3 and 2-4) to give a clearer picture of the entire BES market in a given year.

BES Market Penetration Estimates

Table 2-3 shows the estimated penetration of BES into the electricity provider industry. Sales are projected to climb from about $24 million in 2000 to about $287 million in 2010.

Table 2-4 shows the estimated penetration of BES for electricity end users. These results are based on projections given to Frost & Sullivan by BES suppliers. BES revenues in this segment are forecast to be about $372 million in 2000 and about $434 million in 2010.

Primary Market Drivers

Power quality was already identified by respondents as the major application for BES. This application will probably become even more important as electronics are increasingly used in businesses and global competition places a greater emphasis on avoiding downtime. BES is already used in this application in the form of existing uninterruptible power supply (UPS) systems and serial power systems.

Distributed generation is another driver of the BES market. BES's modularity makes it more appropriate for deployment in distributed sites. Although not many distributed generation projects are currently being conducted, the number of these projects should increase in the future.

BES is a technology that does not produce noise or harmful emissions. It can be used in settings and environments where current generation technologies would be difficult or impossible to site. Electricity providers cited these benefits as some of the major advantages of BES.

Table 2-2. BES: Value-Added Applications (30 Companies), 1996.

Application	Times Application Mentioned
Area/Frequency Control	3
Black Start	1
Customer Demand Peak Reduction	5
Distribution Facility Deferral	6
Emergency Shutdown Power	1
Frequency Control	1
Frequency Regulation	2
Generation Capacity Deferral	5
Generation Dispatching	4
Load Conditioning	1
Load Following	1
Load Leveling	10
Out of Step Prevention	1
Peak Reduction	2
Power Quality	14
Reliability	12
Renewables	5
Spining Reserve	8
Transmission Facility Deferral	5
Transmission Line Stability	2
Transmission Stability Enhancement	2
Transmission VAR Support	2
UPS	10
Voltage Regulation	7

Another advantage of BES cited by electricity providers is the elimination of fuel supply issues associated with generation technologies. This is because BES, by definition, does not require fuel.

Growth in the use of renewable energy should also drive the BES market. BES can be used in conjunction with renewable energy sources to "firm" electric power delivery from these sources. For example, BES could store power generated from solar generation to maintain a constant power output even at night.

BES Cost Improvements Desired

The first and foremost conclusion of this study is that an overwhelming consensus exists among the electricity providers surveyed that significant improvements in BES cost profiles are needed.

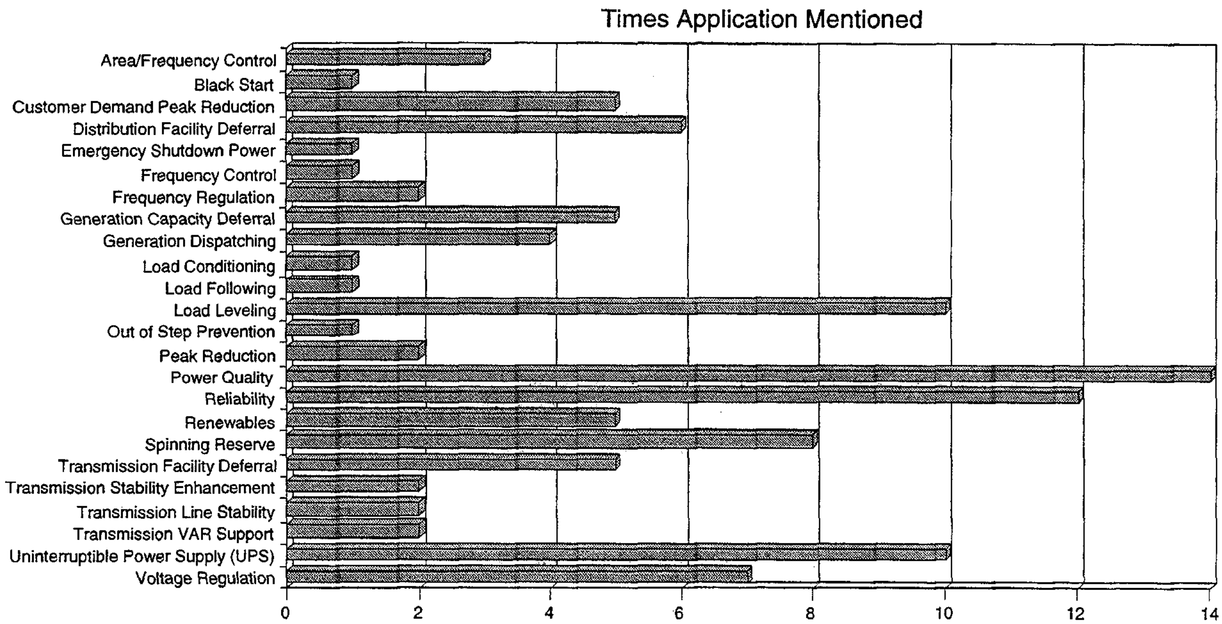


Figure 2-6. **BES: Value-Added Applications (30 Companies), 1996.**

Table 2-3. BES Market: Penetration Statistics Among Electricity Providers (U.S.), 2000, 2005, and 2010

Year	MW	($Million)
2000	27	24
2005	215	129
2010	573	287

In particular, issues pertaining to the capital cost of BES are considered paramount. Currently available per-kilowatt BES costs run two to three times the per-kilowatt cost of combustion turbines. Maintenance costs are also of interest to electricity providers. These costs include not only the actual costs of maintaining a BES but the perceived costs as well. These perceived costs can best be thought of as the "headaches" that respondents expect from a BES system. For example, several electricity providers stated in their responses that even though their organizations had no direct experience with BES, they had heard that the maintenance issues associated with the batteries in a BESS made the cost prohibitive.

The results of the survey also show that electricity providers desire improvements in BES energy density, maintenance characteristics, and life span. These technical issues are secondary to BES cost issues, although they are important in their own right. Energy density affects capital cost and the use of BES in some applications and sites. Maintenance issues center on improvements in BES battery technology. To better offset high capital costs and be more competitive with other distributed generation technologies, current expected BES life spans of 6 to 10 yr must be improved.

The Puerto Rico Electric Power Authority (PREPA) system was cited as a success. The PREPA system was actually chosen over combustion turbines, which seems

Table 2-4. BES Market: Penetration Statistics Among Electricity End Users (U.S.), 2000, 2005, and 2010

Year	MW	($Million)
2000	496	372
2005	805	443
2010	965	434

to be the greatest threat to BES's success. However, even in the PREPA case, the utility itself had to perform the project integration, using equipment from several manufacturers, including some that will not offer those products in the future.

The result is a successful system, but one that no BES supplier is likely to provide to customers. Because nobody but PREPA has "ownership" of the product in use at PREPA, no organization is marketing it. This is the case even though the PREPA frequency regulation/ spinning-reserve application is one that many utilities in the United States need and might be interested in.

The BES market is currently developmental and the industry faces significant challenges. Nonetheless, the results of this study indicate that a market for BES at the electricity provider level does exist. This market is currently self-perpetuating at the national level, but at a lower than desired level of activity.

Projects such as those currently planned in Puerto Rico and Alaska should continue into the foreseeable future. With the development of better BES technologies and the resolution of concerns and issues, the BES market has the potential to be significantly larger.

Storage System Cost Study

The purpose of the original contract, which was placed with Sentech, Inc., was to conduct a cost analysis of energy storage systems for electric utilities that would document the cost of battery storage systems built and installed to date. As the battery storage systems portion of the study was completed, the scope of the study was redefined to require a cost comparison and projection on all storage technologies, including batteries, FES, and SMES. To accomplish this task, a survey questionnaire was designed to obtain all relevant cost information from a select cross section of industry leaders in the areas of batteries, flywheels, and SMES.

For existing battery storage systems, such as those of the Chino substation and PREPA, the distribution of subsystem costs is not well understood. This made it difficult to compare project costs on a uniform basis. The Opportunities Analysis study acknowledged this difficulty and recommended a standardized cost structure that would make it easier to conduct uniform project cost comparisons. Due to the age of some of the earlier battery demonstration projects, such as those at Chino and Crescent, the corporate history that reports the true system costs is rapidly disappearing. The Storage System Cost Study was initiated with three objectives:

1. Gather the most reliable cost estimates for all the existing battery projects in the U.S.

2. Estimate the current capital cost for storage systems using all three storage technologies: batteries, flywheels, and SMES.

3. Estimate the system cost reduction that may be realized through future reductions in subsystem costs.

Status

Utilities and suppliers were contacted to ascertain the costs of projects according to the detailed categories suggested by the Opportunities Analysis study. The expectation was that this standardized format could be used for future storage projects, and that it could provide a basis for comparison of different storage technologies.

In order to maintain supplier confidentiality, detailed costs were aggregated into three categories: the storage subsystem, the power conversion subsystem, and the balance of plant. Some of the data collected provides cost breakdown in a percentage form. BES project cost information was obtained for the following projects:

1. The BES system at the Sabana Llana substation in Puerto Rico (PREPA);

2. The BES system at the Chino substation in Southern California (Chino);

3. The proposed but later postponed BES project in the service territory of Hawaii Electric Light Company (HELCO);

4. The BES system at the lead smelting factory in Vernon, Southern California (Vernon);

5. The BES project in the service territory of Metlakatla Power & Light in Alaska (Metlakatla);

6. The BES installation at the Crescent Electric Membership Cooperative in Statesville, North Carolina (Crescent Electric);

7. The San Diego Trolley Project in the San Diego Gas and Electric service territory (SDG&E); and

8. The BES system at Berlin Power and Light in Berlin, Germany (BEWAG).

In addition, the system costs for the PQ2000 power quality and PM250 BES product lines were obtained. The BEWAG and SDG&E systems are not in operation now, and the HELCO project was never built. The HELCO costs listed are estimated project costs.

The SSD® micro-SMES product line developed by Superconductivity, Inc. (SI) has been installed at several facilities, and its cost breakdown is discussed. The cost of the IPQ-750 micro-SMES developed by Intermagnetics General Corporation is also presented. Preliminary cost data for the larger, 1350-MJ (375-kWh) SMES proposed at Anchorage is also presented.

Small-scale, low-loss (compared to conventional flywheels), high-speed FES systems are expected to be introduced to serve power quality applications. Prices of such systems, as quoted by vendors, and a simplified direct cost estimate developed by a vendor for larger systems are provided. The ratings and operating characteristics of the only operational FES system investigated at the Usibelli coal mine is also discussed.

Preliminary results verify that there are several applications in the electric utility industry in which the three storage systems considered in this study can be used. Currently, BES and SMES systems are being used for niche applications. Significant cost reductions are required if these technologies are to gain widespread use in the electric utility sector.

Though prototypes of small power-quality FES systems have been produced, they have not yet been demonstrated at any commercial facilities. FES systems exhibit attractive volumetric energy density and potentially long life. Moreover, since FES could be placed underground, it potentially has a very low footprint. These features warrant an early demonstration of the technology so that firm cost/benefits can be estimated.

Current costs of \$1200-1500/kW are common for BES systems with 1-2 hr of storage capacity. The batteries and the PCS, however, contribute only about 50% of the cost. Since both the lead-acid battery and the PCS are mature technologies, a cost-reduction of only 10-15% for these components is expected over time. The bulk of the cost reduction must come from the remaining 50%, which is comprised of three components:

- Facilities to house the equipment: 20%
- System design and integration: 10%
- Transportation, finance charges and taxes: 15%

The focus of system suppliers is to develop a factory-assembled, modular, transportable BES system to reduce the costs associated with facilities and engineering services. ACBC has been a leader in promoting the concept successfully. Other vendors are also seriously considering standardized modular designs.

The present cost structure of the three storage technologies makes them uncompetitive for applications that require both high power (MW scale) and long durations (>1 hr). It is becoming increasingly clear that storage technologies cannot be viewed as a generation technology. With fast-acting power conversion and control systems, and the rapid response capability of the storage system, it appears that energy storage systems are best suited for dynamic system operation.

This is especially true for SMES, as energy available in superconducting magnets, unlike batteries, is independent of its discharge rating, which makes them attractive for high-power and short-energy-burst applications. The preliminary estimates of the storage component cost of the Anchorage SMES project is \$54,000/kWh. This is the first large superconducting magnet being built for utility applications. Significant cost reductions will be required if SMES is to be viable for utility applications on a wide scale, and potential for such cost reduction exists for this advanced technology system.

BES and SMES are more competitive for power quality applications for two primary reasons. First, the power quality problems experienced by industry are very similar in nature, and therefore a uniform product line can be developed and marketed, achieving economies of scale. Second, because of the large economic losses caused by power supply perturbations, industries are willing to invest substantial amounts in equipment to shield them from these perturbations. The increasing sensitivity of customer machinery to these disturbances presents a growing market for protection systems. Cost projections indicate a 10-20% cost reduction for BES, and a 30-40% reduction for SMES systems in this application. Cost reductions through technology improvement and volume manufacture are essential for the competitiveness of all the technologies and system components.

The power conditioning system (PCS) presently costs ~$300/kW in energy storage systems and is not projected by industry to drop by more than 10%. On the other hand, the power quality application market expects the price to drop by 25 to 40%. The concept of the modular PCS is now being promulgated as a way to drive PCS cost down. A modular PCS is composed of many small converters that are networked in parallel (using software) to achieve the same power rating of a single large converter, but benefits through the economies of mass production. The individual units, if designed to operate with a sufficient degree of autonomy, can be rescaled dynamically. This offers the advantage of redundancy and on-line maintenance. High efficiency can be maintained at low-power throughputs, because only the minimum required number of power converters need to be energized. Hence modular PCSs are expected to provide solutions at a lower cost with better redundancy, reliability, and efficiency.

Note that when comparing the three technologies for customer-end power quality applications, the energy storage capacity is specified in megajoules, while kilowatt-hours were used for all other applications. Tables 2-5 and 2-6 summarize the costs of the projects that are currently using these three technologies, as well as the storage system products.

PV Battery and Charge Controller Market and Applications Survey

This study is being conducted using a survey designed and implemented under a contract with ASU. The survey is being sent to industry representatives who design and integrate stand-alone PV systems. It will attempt to determine what types of and how many batteries are currently used in the stand-alone PV market. The survey also polls system integrators on their method of specifying batteries and charge controllers for the systems they design. ASU performed a similar, related survey in 1992 for SNL's PV group.

Status

The contract to conduct a PV battery and charge controller market and applications survey was placed with ASU in June of 1995. The purpose of the survey was to:

- Quantify the market for batteries shipped with (or for) PV systems in 1995, and estimate the PV battery market through the year 2000.
- Quantify the PV market segments by battery type and application for PV batteries, and establish present and future battery-use patterns.
- Characterize and quantify the charge controllers used in PV systems and find out what the controller industry's perception is of their role within the PV and battery subsystem industries, and what their contribution to large and small PV battery systems might be.
- Characterize the operating environment for energy storage components in PV systems.
- Provide an information base that bridges the communication gap that currently exists between battery manufacturers, PV system designers/users, and charge controller manufacturers.

To meet the stated purpose of the survey, the contract SOW directed ASU to develop a survey to solicit industry perspectives, responses from which would be compiled in an electronic database and used as a trend analysis tool. SNL also provided the following criteria defining the size and number of design companies and manufacturers to be surveyed:

- Survey up to 30 PV system designers. A broad response from PV system designers, representing all areas of the electrical energy industry that use storage and PV as subsystems, was anticipated and received. The following criteria were applied in the selection of PV system design participants:
  - Twenty small system integrators (SoloPower size)
  - Seven+ (7 min-10 max) large system integrators (Photocomm size).

Table 2-5. Cost of Projects and Products–Energy Storage Systems

Project/ Product	Description of System	Cost of Storage Subsystems - constant 1995$			Total Cost - constant 1995$		
		Storage	PCS	BOP	$/kW	$/kWh	(000s of $)
PREPA[a]	20-MW/14-MWh BES	22% ($341/kWh)	27% ($294/kW)	51%	1,102	1,574	22,042
Chino[b]	10-MW/40-MWh BES	44% ($201/kWh)	14% ($258/kW)	42%	1,823	456	18,234
Hawaii Electric - HELCO[c]	10-MW/15-MWh BES	34.5% ($304/kWh)	18.5% ($212/kW)	47%	1,166	777	11,660
Vernon[d]	3-MW/4.5-MWh BES	32% ($305/kWh)	19% ($275/kW)	49%	1,416	944	4,250
Metlakatla[e]	1-MW/1.2-MWh BES	-	-	-	-	-	1,200
Crescent[f]	500-kW/500-kWh BES	41% ($518/kWh)	40% ($506/kW)	19%	1,272	1,272	636
SDG&E[g]	200-kW/400-kWh BES	16% ($658/kWh)	23% ($1,855/kW)	61%	8,150	4,075	1,630
PM250[h]	250-kW/167-kWh BES	20% ($449/kWh)	50% ($750/kW)	30%	1,500	2,245	375
Anchorage Municipal L&P[i]	30-MVA/375-kWh SMES	45%	45%	10%	1,467	117,333	44,000

a. The PREPA plant is comparable to Chino, but was built 6 years later. The PCS at PREPA was an improved version of the one installed at Chino—both supplied by GE. Balance of plant included $0.6M for load interface, $1M for finance charges, $4.7M for building the facility, and $1.8M for services.
b. The balance of plant includes $0.15M for load interface, $3.8M for facility, and $1.7M for services.
c. Though this plant was never built, the costs given were those of the winning bid submitted by GNB/GE. Energy rating specified @ a 3-hr discharge.
d. Detailed costs are provided in Appendix C of *Cost Analysis of Energy Storage Systems for Electric Utility Applications* (SAND97-0493).
e. Individual cost of each subsystem was not obtainable.
f. Installed at the Crescent Electric site in 1987-88. The balance of plant is exclusively the cost of the $81,000 building Crescent Electric built to house the BES—the only cost Crescent Electric incurred.
g. The San Diego trolley project was a demonstration project and was overengineered in many respects.
h. The PM250 is a modular power management system product line developed by AC Battery Corporation. Up to 50% cost reduction is anticipated at a 40-MW/annum production volume.
i. Construction of this demonstration project is about to commence. Balance of plant includes the cost of constructing the building that will house the system.

Table 2-6. Cost of Projects and Products–Power Quality Systems

Power Quality Products	Description of System	Cost of Storage Subsystems - constant 1995$			Total Cost - constant 1995$		
		Storage	PCS	BOP	$/kW	$/MJ	(000s of $)
PQ2000®[a]	2-MW/10-sec Power Quality BES	9%	65% ($316/kW)	26%	495	49,450	899
SSD®[b]	8-MJ Power Quality SMES	30%	30%	40%	300 - 600[f]	300,000	2,400
IPQ-750®[c]	750-kVA/6-MJ SMES	--	--	--	1,300	170,000	1,000
20C1000®[d]	1-kW/7.2-MJ FES				2,000	278	2[g]
WFC[e]	1.5-kW/0.36-MJ FES	--	--	--	6,666	27,778	10[h]
	20-kW/10.8-MJ FES	--	--	--	2,650	4,907	53[h]

a. The PQ2000 was built by AC Battery Corporation. A high discharge rate distorts battery costs when specified in $/kWh. The PCS cost includes the converter and the static switch. Balance of plant includes cost of delivery, installation and startup. The energy stored in the 2-MW system for 10 sec is equivalent to 20 MJ for purposes of comparison with SMES power quality systems.

b. The SSD units were developed by Superconductivity, Inc. Because the duration of operation is limited by the energy stored in the superconducting magnet, an 8-MJ system can have multiple ratings.

c. Intermagnetics General Corporation product cost projections. Estimated annual operating cost $55,000. Like most other SMES products, this unit has a range of operating characteristics. Compared to the SI system, the IPQ-750 has a smaller converter.

d. A product developed by SatCon Technology Corporation. The 1-kW/2-kWh flywheel rotor is being developed by SatCon for telecommunication applications.

e. The World Flywheel Consortium product line.

f. Assuming an 8-MW rating for 1 sec of protection and a 4-MW rating for 2 sec of protection.

g. Targeted cost for production volumes in the lower thousands, additional cost of $500-$1,000 expected to be incurred for installation.

h. The price for a single product. Lower costs are anticipated for volume purchase.

- Survey 10 battery manufacturers, representing flooded lead-acid (calcium and antimony chemistries) and VRLA technologies. Manufacturers of other rechargeable technologies may also be considered for the survey.
- Survey 10 charge controller manufacturers (5 large, 5 small) representing a cross section of typical charge controllers currently in use for PV applications.

During the first quarter of FY96, the surveys were defined and assembled by a team of ASU and SNL battery and PV engineers. During that time, a list of participants was identified. The survey was to cover calendar year 1995, which required that they be sent out to the selected participants early in the second quarter of FY96. The surveys were sent out and returned in the second quarter of FY96.

In the same quarter, a meeting was held at ASU where the initial responses from the survey were reviewed. Of the 29 PV system integrators who were polled in the survey, over 70% returned their surveys. In addition, 9 of 10 battery manufacturers and 8 of 10 charge controller manufacturers responded, indicating a high level of interest in the information that was being collected in the survey. During the second quarter, the data was posted to a PC database where it was used to determine the statistics for the survey. It was also correlated with data from a 1992 survey to develop trend data that could be extrapolated to predict growth in battery sales in the PV marketplace.

Initial review of the information provided by charge controller manufacturers indicated that, in general, old attitudes about batteries being "just batteries," to be regarded much like automotive batteries, were changing. The new evidence indicates that the charge controller manufacturers are envisioning batteries in cycling applications where charge control is essential to maintaining a good state of health (SOH) for PV batteries. New control schemes were being implemented to more precisely control the charge process for the various lead-acid technologies and chemistries. The new attitude exemplified by these changes is expected to result in an overall improvement in battery performance in PV systems.

Under the contract, results from the survey were scheduled for publication by June 30, 1996. However, an inordinate amount of time was required to eliminate conflicts in data reported, resulting in an initial contract extension to September 6, 1996. A no-cost second extension was issued in early September to the end of the first quarter of FY97 to allow for the final verification of data that appeared to be inconsistent. Several new tasks aimed at refining the data for reporting purposes were also included in the initial extension. A top-down analysis was requested to indicate the actual number of batteries in use worldwide for PV applications.

The final report, which will be published and distributed as a SAND document, will serve as an information exchange tool among the three elements of PV energy storage systems: PV system integrators, battery manufacturers, and charge controller manufacturers. Names, companies, and phone/fax numbers identified in the report will enable direct communications among key participants in each of the three industries.

Respondents to the survey indicated a need for continued support by SNL in the collection and dissemination of information related to PV system energy management. Information exchange and information dissemination is most effective when done on a regular basis. There is a significant benefit to SNL's continuing to serve as the focal point for PV energy system information generation, collection, and distribution by (1) expanding the contact list developed in the course of the survey to all interested individuals; (2) advancing Internet access to existing battery storage information as a means for industry to ask questions and contribute information; and (3) disseminating quarterly and annual information regarding PV industry initiatives.

Top-Down Market Analysis

Until the Top-Down Market Analysis was performed, there was no way of knowing how many batteries were being sold for PV applications.

The following summary of the market analysis to a large extent represents a worldwide market and therefore can be extrapolated. However, the data does not provide a means to estimate total PV battery sales for either the U.S. or the worldwide market. The analysis provides an estimate of total PV battery sales worldwide and in the U.S. by all purchasers of PV batteries, not just system integrators.[1]

[1] The 21 system integrators that responded to this survey represent only a fraction (14%) of the U.S. PV battery market and a much smaller fraction of the worldwide PV battery market (1.6%). One reason why the 21 system integrators have a small share of the total U.S. market is because the PV battery market is fragmented with many end users purchasing from local battery distributors. The end user may be, for example, an electric or gas utility, a telecommunications company, the Department of Defense, a recreational vehicle owner, or a remote home owner.

The top-down analysis is based on a rule of thumb that provides an estimate of the number of batteries used for each 50 W (peak) of modules used.[2] Since the number of PV watts shipped each year (both U.S. and worldwide) is well known and published by recognized PV marketing experts, it is a straightforward process to estimate the total number of batteries installed in PV systems each year.

Worldwide PV module shipments in 1995 were approximately 78 MW,[3] with about 67 MW being used in stand-alone applications (about 11 MW were used in grid-connected and consumer applications).[4] Water pumping, a segment of the stand-alone market, often does not use batteries, so the 67 MW will be adjusted downward to 64 MW, which represents PV module sales in systems that included batteries. As a rule of thumb, on average, one 12-V 100-Ah battery (i.e., 1.2 kWh) is used for each 50 W of PV modules.

- The total worldwide sales of PV batteries in 1995 was (64 MW/50 W) × 1.2 kWh = 1,536,000 kWh.

Additional batteries were sold during 1995 to replace batteries that reached end of life in existing PV systems. Assuming a typical battery life of 5 yr and that all PV system batteries installed in 1990, 1985, and 1980 were replaced (934,000 + 291,000 + 200,000 kWh), then a total of 1,425,000 kWh of batteries were replaced in 1995.

The total of new-system batteries in 1995 (1,536,000 kWh) plus the replacement batteries (1,425,000 kWh) equals 2,961,000 kWh of PV system battery sales. As indicated in Table 2-7, the average cost for a kilowatt-hour in 1995 was $102 per kWh (wholesale).

- The worldwide wholesale value for PV batteries shipped in 1995 was $302M.

The approximate values that went into this calculation will limit the accuracy to about ±25%, so that an appropriate range for wholesale dollar value would be $226M to $378M.

It is estimated that about 11.5% of the total 64 MW of stand-alone PV were installed in the U.S. in 1995.[5] Therefore, total PV battery sales in the U.S. were 11.5% × 2,961,000 kWh or 340,515 kWh (or about 11.5% × $302M = $34.7M).

- This indicates that the 21 system integrators control about $4.76M[6]/$34.7M = 14% of the U.S. PV battery market (in terms of dollar sales).

Using the same methodology to calculate the newly installed capacity each year (not counting replacement batteries), it is estimated that:

- Approximately 10,519,000 kWh of batteries are currently installed in PV systems worldwide.

Table 2-8 provides a summary of the worldwide top-down market data for 1995, while Table 2-9 provides a similar summary for the U.S. market. Data for the years 1991 and 2000 are also included in these tables for comparison.

Incorporation of BES into NEMS

Sentech, Inc., published a study addressing how BES can be incorporated into the EMM of the NEMS in July 1996. The purpose of the study was to assess the feasibility of, and to make recommendations for, developing methodologies to incorporate storage in stand-alone dispatchable units.

Status

The study concluded that three possible avenues exist for including storage technologies within the EMM. The first is to add storage technology as a peak generation candidate in the Electricity Capacity Planning (ECP) submodule of EMM. This option, which has been considered previously, was eliminated due to overwhelming evidence indicating that the difference in the marginal cost of production between peak and off-peak periods is not large enough to warrant investment in BES systems. The second method considers storage technologies as the demand-side management (DSM)

2 The widely accepted rule of thumb is that for every 50 W (peak) of PV modules used in a PV system, approximately 1.2 kWh of battery is used (e.g., one 12-V, 100-Ah battery). This rule of thumb is sometimes used to estimate the quantity of batteries for a "typical" PV system. It is estimated that the uncertainty of this rule is ±20%.

3 Based on averages of data from conversations with Bob Johnson of Strategies Unlimited (May 1996) and Paul Maycock of *PV News* (February 1996). Johnson and Maycock are two of the leading PV industry experts and have provided technology and market reports (including historical and forecasted PV sales data) for about two decades.

4 Consumer applications: small "expendable" products such as solar-powered calculators, toys, and walk lights (<5 W peak).

5 Based on estimates of 12.8% by Paul Maycock (*PV News*) and 10.6% by Bob Johnson (Strategies Unlimited) during telephone conversations November 1, 1996.

6 See Table 2-7.

Table 2-7. Totals for All Batteries [1]

Technology	1995						
	# of Units	% of #	$ (Wholesale)	% of $	kWh	%-kWh	$/kWh
Valve-Regulated	16,846	64%	$3,390,782	71%	26,524	57%	$128
Flooded-Vented	9,462	36%	$1,370,060	29%	20,012	43%	$68
Total	26,308	100%	$4,760,842	100%	46,536	100%	$102

1 Prices are for battery modules only, i.e., prices do not include balance of system hardware.

Table 2-8. Worldwide Top-Down PV Battery Market Estimates

		Units	1991	1995	2000
a	Worldwide PV module shipments, stand-alone systems with batteries.[1]	MW	44	64	134
b	50 W (peak) of new PV module installation. [b = (a/50) × 1.2 × 1000]	MWh	1056	1536	3216
c	PV replacement batteries based on an average battery life of 5 yr.[1] (See text for methodology.)	MWh	618	1425	2961
d	Total PV batteries; new installations plus replacement batteries for the year indicated. [d = (b + c)]	MWh	1674	2961	6177
e	Total PV batteries (units) based on a "typical" size battery of 1.2 kWh (e.g., 12 V, 100 Ah). [e = d/(1.2 × 1000)]	No. Millions	1.40	2.47	5.15
f	Total dollar value of PV batteries based on $102/kWh (see Table 2-7). [f = d × 102/1000]	$, Million	171	302	630
g	Total installed capacity of PV batteries from 1980 to 1991, 1995, and 2000.[1] (See text for methodology.)	MWh	5309	10,519	22,761
h	Total installed capacity of PV batteries from 1980 to 1991, 1995, and 2000 (1.2-kWh "typical" size). (h = g × 1000/1.2)	No. Millions	4.42	8.77	18.97
i	Total installed capacity of PV batteries from 1980 to 1991, 1995, and 2000 ($102/kWh). (i = g × 102/1000)	$, Million	542	1073	2322

1 These data are based on conversations with Bob Johnson of Strategies Unlimited in May 1996 and with Paul Maycock of the publication *PV News* in February 1996. Years 1991 and 1995 are based on historical data; data for the year 2000 are based on projections by Johnson and Maycock. Johnson and Maycock are two of the leading PV industry experts and have provided technology and market reports (including historical and forecasted PV sales data) for about two decades.

Table 2-9. U.S. Top-Down PV Battery Market Estimates

		Units	1991	1995	2000
a	U.S. PV module shipments, stand-alone systems with batteries.[1] [a = .115 × (a of Table 2-8)]	MW	5.06	7.36	15.41
b	PV batteries shipped, based on 1.2 kWh of batteries per each 50 W (peak) of new PV module installation. [b = (a/50) × 1.2 × 1000]	MWh	121	177	370
c	PV replacement batteries based on an average battery life of 5 yr.[1] (See text for methodology.)	MWh	71	164	341
d	Total PV batteries; new installations plus replacement batteries for the year indicated. [d = (b + c)]	MWh	193	341	710
e	Total PV batteries (units) based on a "typical" size battery of 1.2 kWh (e.g., 12 V, 100 Ah). [e = d/(1.2 × 1000)]	No. Millions	0.16	0.28	0.59
f	Total dollar value of PV batteries based on $102/kWh (see Table 2-7). [f = d × 102/1000]	$, Million	20	35	72
g	Total installed capacity of PV batteries from 1980 to 1991, 1995, and 2000.[1] (See text for methodology.)	MWh	611	1210	2618
h	Total installed capacity of PV batteries from 1980 to 1991, 1995, and 2000 (1.2-kWh "typical" size). (h = g × 1000/1.2)	No. Millions	0.51	1.01	2.18
i	Total installed capacity of PV batteries from 1980 to 1991, 1995, and 2000 ($102/kWh). (i = g × 102/1000)	$, Million	62	123	267

1 These data are based on conversations with Bob Johnson of Strategies Unlimited in May 1996 and with Paul Maycock of the publication *PV News* in February 1996. Years 1991 and 1995 are based on historical data; data for the year 2000 are based on projections by Johnson and Maycock. Johnson and Maycock are two of the leading PV industry experts and have provided technology and market reports (including historical and forecasted PV sales data) for about two decades.

option within the Load and Demand-Side Management (LDSM) submodule and allows storage to compete with other DSM technologies. Unfortunately, this study indicates that the LDSM submodule must be further refined prior to considering how to incorporate it into BES systems. The interaction between EMM and the remainder of NEMS is illustrated in Figure 2-7. The ECP submodule evaluates generation technology options that are needed to meet future demand for electricity and comply with environmental regulations. These options include investments in new utility and nonutility plants (excluding cogenerators), demand-side management programs, and pollution control equipment.

The third possibility is to integrate storage with renewable technologies in order to make them more reliable from a system operations perspective and to command better prices for the energy they generate. The study recommends the analytical work be carried out for this third option of integrating storage with renewable technologies and that a thorough assessment be made of the potential benefits storage can bring to renewable generation technologies. Formulation of costs associated with the integrated plant and an assessment of benefits that could be recognized within the existing NEMS framework will have to be undertaken to evaluate the net gain.

If the additional cost of integrating storage with renewable generation technologies is lower than the additional benefits it can bring about, the competitiveness and penetration of renewable technologies will be increased. NEMS can model an integrated renewable unit as another renewable technology with an increased capital and operations and maintenance (O&M). If the additional benefit stream is not accounted for, this integrated unit, when competing against other renewable

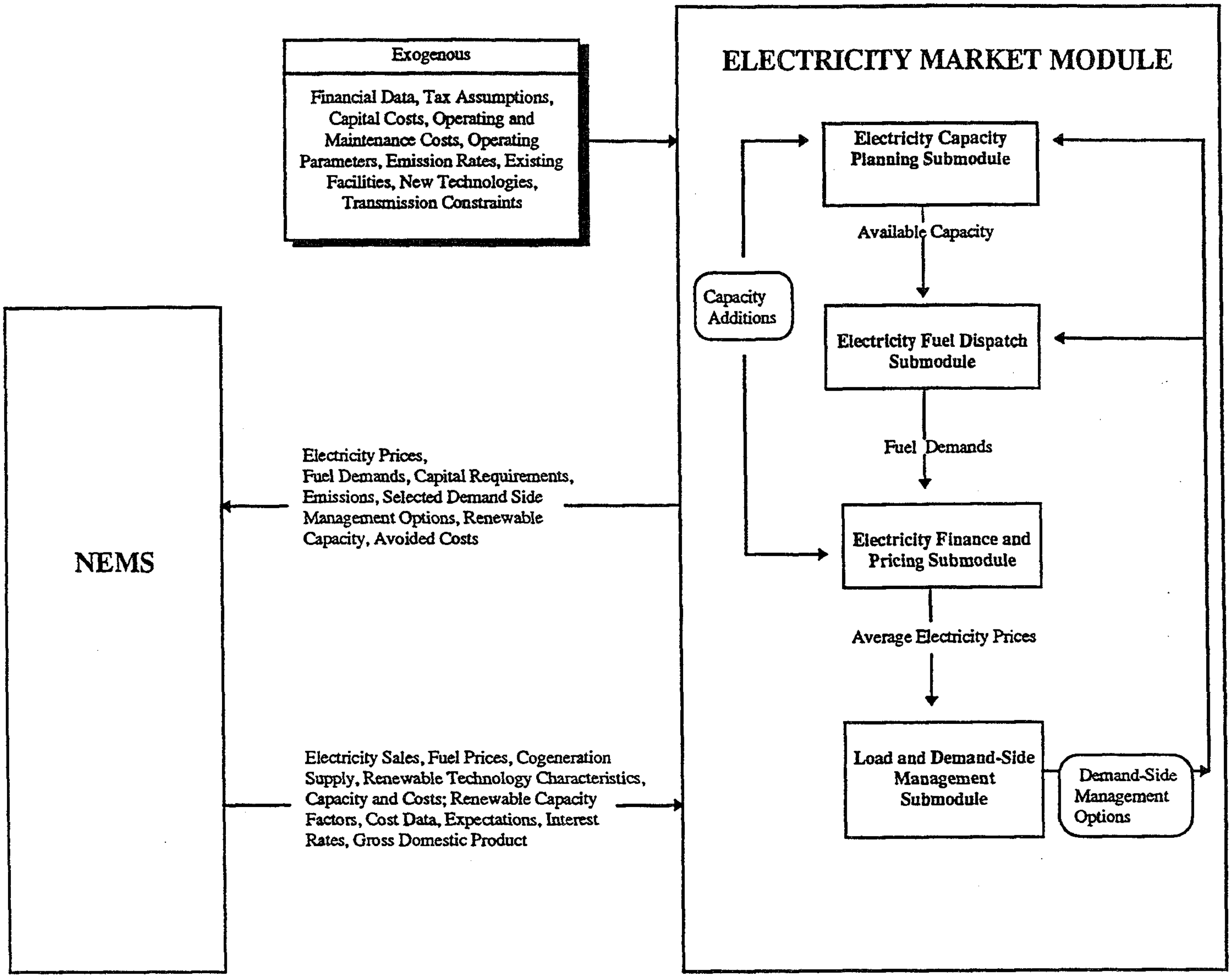


Figure 2-7. Structure of the Electricity Market Module.

generation technologies for market share, will not be as competitive. The additional benefit stream, which NEMS has the potential to incorporate, includes (1) the benefits associated with dispatchability of renewable units at the system dispatcher's discretion (increased capacity credit) and (2) the ability of an integrated renewable unit to store energy and make it available when it can garner the highest price.

Modeling storage as a peak dispatchable capacity in the EMM is relatively straightforward. Once the relevant performance and cost characteristics of the battery plant are estimated and provided as inputs to the ECP, the storage plant is considered just another peak generation option. The ECP selects the appropriate mix of generation plants with the lowest average cost to meet the demand growth of the system. The storage plant must be able to compete with other generation options on the basis of the low average cost.

As a practical matter, additional programming will be required to model the recharging of the storage plant during off-peak periods. The period of lowest marginal energy cost would have to be identified, and the corresponding capacity would have to be added to the load-duration curve for that period.

This exercise would provide an estimate of the national benefits of load leveling. Such estimates have already been made, and it is generally accepted that the load-leveling benefits of energy storage are not that large. The EMM does not provide the necessary framework to evaluate other T&D-related benefits associated with storage technologies, such as provision of spinning reserve and frequency regulation.

Storage potentially adds value to renewable energy systems by making them more dispatchable. NEMS, with modifications, can estimate the value that energy storage adds to renewable energy systems and project the penetration such integrated systems could achieve.

Storage provides the flexibility to introduce a time shift between renewable energy generation and consumption. The marginal cost of electricity generation to meet demand is different for each of the 11 load segments of the load duration curve (see Figure 2-8), with segments with higher demand requiring high-cost peaking units. Enabling renewable generation to shift from low-demand to high-demand periods allows renewables to demand higher prices, increasing the value of renewable generation. The cost differential between high- and low-demand periods within NEMS varies by a factor of 2. Proper analysis of this differential must be carried out in order to quantify this benefit.

Another benefit associated with integration of storage is the ability of the integrated unit to supply reliable power on demand. The ability of generating units to supply electricity on demand is crucial for the reliable operation of the power system. Storage provides the means by which an intermittent resource can be stored and made available on request with certainty. At present, some of the wind turbines within the Renewable Fuels Module (RFM) are assigned capacity factors that are as high as 37.5% of the nameplate power rating of the turbine generator. However, it is customary for utilities to assign lower capacity credits (15-20%) to wind turbines for operational purposes. Storage will provide the means by which to increase the capacity credit to 100% of the generator's nameplate power rating.

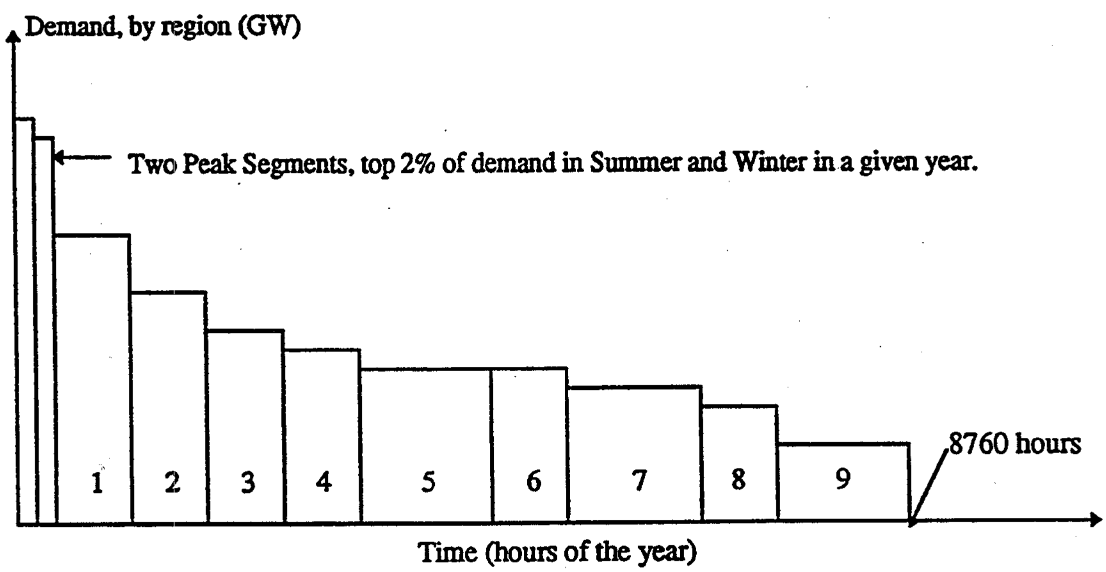


Figure 2-8. Construction of the Load Duration Curve.

3. Component Research and Development – Zinc/Bromine Battery Development

Introduction

The ESS Program has acknowledged the potential for utility BES and began supporting programs to develop advanced battery systems such as the zinc/bromine in the 1980s. The potential advantages of zinc/bromine technology include high specific energy (70-80 Wh/kg), rapid recharge (2-4 hr), deep-discharge capability (100%), a finite self-discharge, and a built-in thermal management system. Inexpensive raw materials and mass production manufacturing techniques have resulted in a battery system that is potentially low in cost ($150/kWh) and has a stack replacement cost of $50/kWh. Initially, the zinc/bromine development project emphasized component development and improved manufacturing techniques, but the emphasis has since shifted to battery system integration and field evaluation.

The zinc/bromine battery development project is being completed through an in-kind cost-sharing contract with ZBB. The objectives of the project are to design, fabricate, and evaluate a zinc/bromine battery system suitable for electric utilities. Phase I of the program demonstrated the soundness of the technology by meeting a number of criteria, including the following:

1. Leak-free battery stacks.
2. Steady long-term operation by achievement of over 100 cycles with less than a 10% drop in energy efficiency, with an overall efficiency of approximately 75%.
3. Six consecutive no-strip cycles.
4. A battery that costs $150/kWh or less.
5. A safer battery, through resolution of safety issues associated with the battery.

In Phase II, a larger electric utility battery stack design was developed while the core technology research continued. The 2500-cm^2 design was selected to reduce the number of stacks required to achieve a higher storage capacity in utility systems; by reducing the number of stacks, system manufacturing costs were also reduced.

The final product of Phase II of the zinc/bromine development program was to be a 100-kWh battery to be tested in a laboratory. A major contract modification was implemented to add integration of a turnkey 100-kWh stand-alone system for testing at the PG&E MGTF in San Ramon, California.

During the course of the contract, substantial progress has been made in the following areas: minimizing leaks, improving battery performance by refining battery components and manufacturing techniques, and interfacing the battery and PCS.

ZBB recently completed a move into a 13,000-sq.-ft. installation in Wauwatosa, Wisconsin. Facilities were prepared at this installation for the manufacturing and testing of zinc/bromine batteries.

Status

100-kWh Deliverable Battery Design

The original 100-kWh deliverable battery consisted of six battery stacks, two electrolyte reservoirs, and a support structure. The SOW for the contract was later changed to require delivery of a self-contained, stand-alone, peak-shaving system to be connected to the utility grid at PG&E. A three-module configuration was selected so that the battery modules could be connected either in series or in parallel. Details on the 100-kWh battery and the progress made in its manufacture will be covered in the following sections.

The demonstration unit consists of a 100-kWh stand-alone system housed in a portable chemical storage vault. It contains three battery modules, each rated at 33 kWh for a 2-hr discharge. Each module consists of two 60-cell, 2500-cm^2 battery stacks connected in parallel, a pair of reservoirs, and an electrolyte circulation system. Photographs of the battery and the Hazmat building are provided in Figures 3-1 and 3-2.

The system is designed to sustain a 200-A discharge for 2 hr at an average of 273 V. The building is divided into four sections: three quadrants contain battery modules and a fourth, isolated quadrant houses the heat exchangers, a bromine scrubber, and electrical panels.

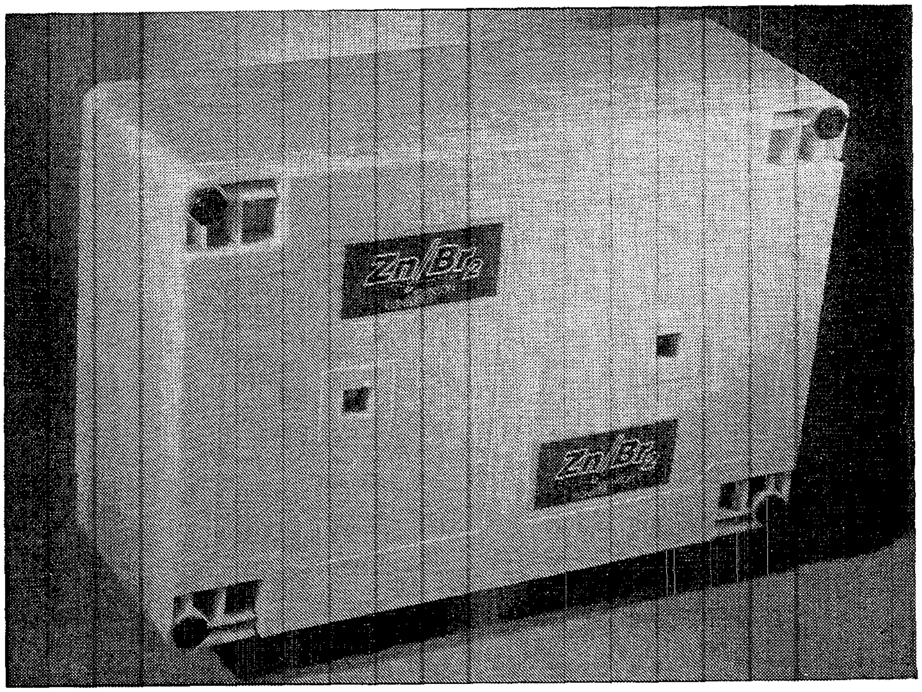


Figure 3-1. Zinc/Bromine Battery Stack, 2500 cm^2, 60 Cells.

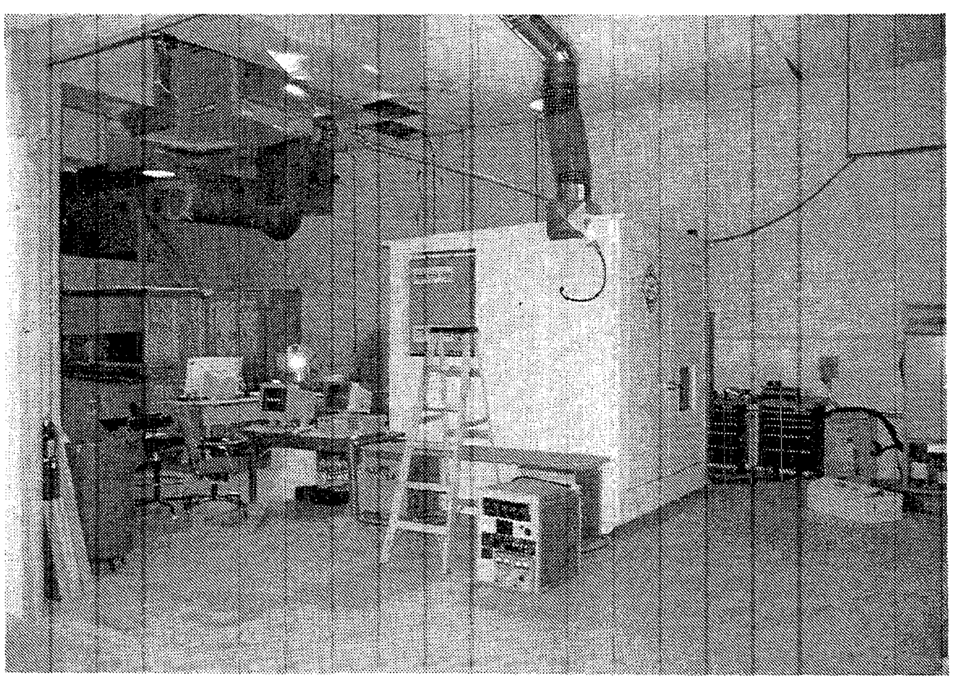


Figure 3-2. Hazmat Building Containing 100-kWh Deliverable.

The building has a spill containment sump in addition to the sumps for the individual modules. Additional safety devices include bromine and hydrogen sensors and an accelerometer for earthquake detection.

The battery system is designed to comply with Zone 4 earthquake requirements. Compliance with these requirements is accomplished by using an epoxy-coated steel frame to support each module; the reservoirs are inserted into the structure of the frame with the two battery stacks located between the reservoirs. The stacks are attached to the frame by plastic-coated steel cords to restrain the stacks in the x, y and z directions in case of an earthquake (see Figure 3-3).

Each reservoir accommodates a recessed sump area in the cover where the pumps are located. The anolyte reservoir uses one pump, while two other pumps are used to circulate both the aqueous catholyte and complexed bromine phases. Brushless DC motors run centrifugal pumps that are mounted vertically inside the recessed area in the reservoir covers. The inlets to the pumps are located below the liquid level in the reservoirs, which eliminates the need to prime the pumps. The majority of the plumbing consists of fused polyvinylidene fluoride (PVDF) that is located inside the reservoir to minimize leakage from the system. Any minor leaks from this plumbing would be contained inside the reservoirs.

The plumbing from the reservoirs to the stacks is reinforced viton, which was chosen because of its flexibility. The entire module is located inside a larger spill containment tray.

Liquid-level sensors are located at the top of each reservoir. These analog sensors are accurate to 0.25 in. and supply data to the battery controller. The data is used to maintain constant electrolyte levels in each reservoir by adjusting pump speeds. Leak sensors are located in the module spill tray and in each reservoir sump area.

The module is designed so that stacks can be electrically connected in either parallel or series configurations. Each module has an open-circuit voltage of 109 V. The battery system specifications for three modules connected electrically in series are provided in Table 3-1.

An extensive data collection system has been developed to verify the need for battery subsystems. Parasitic losses from the pumps, heat exchanger, and control system will be quantified, and a paging system, which automatically activates in the case of a potentially haz-

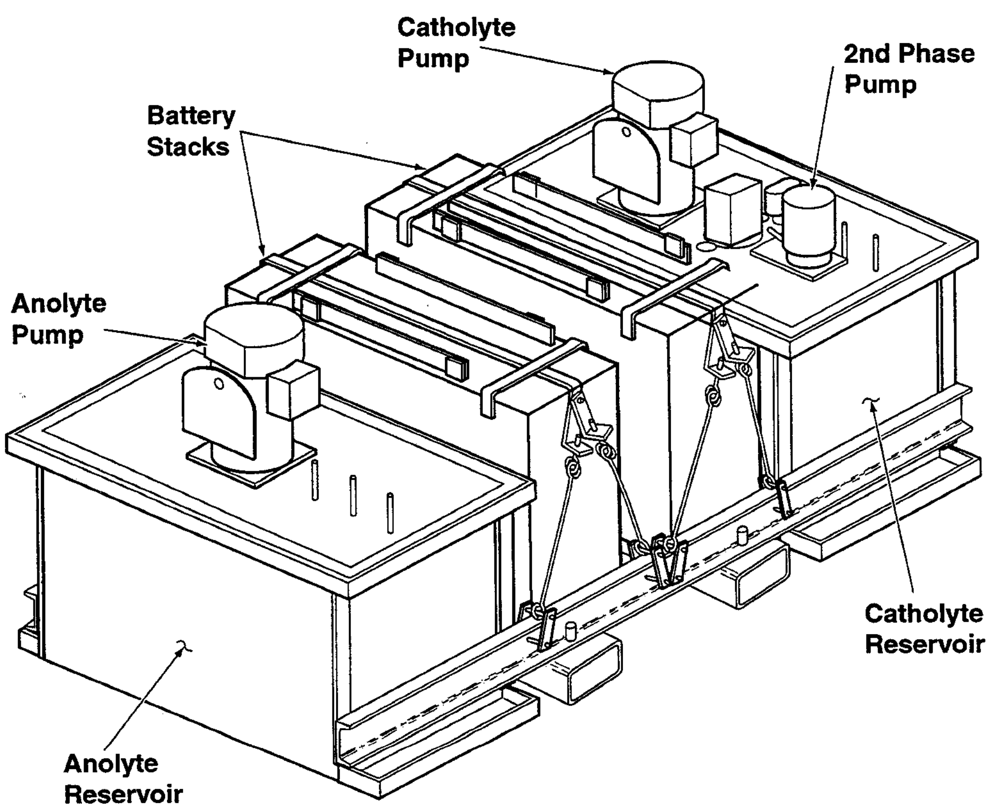


Figure 3-3. Depiction of a 33-kWh Battery Module.

Table 3-1. 100-kWh Battery Specifications

	Typical	Maximum
Charge Voltage	360 V	(378 V)
Charge Current	100 A	(150 A)
Open-Circuit Voltage	328 V	
Discharge Current	100 A	(200 A)
Low-Voltage Cutoff	180 V	
Strip-Current Cutoff	0.5 A	

ardous condition, has been installed. An internal load management system has been integrated into the system by running all of the auxiliary equipment, such as the heater, scrubber, etc., off a 30-A circuit. Therefore, if the scrubber needs to be activated, the heater will be automatically disconnected from the circuit to maintain the 30-A load.

An Ansul-certified fire-suppression system was installed in the Hazmat building. The fire-suppression system consists of a dry chemical and a propellant that distributes the chemical to each of the four quadrants in the building and can be activated automatically by excessive heat in any of the quadrants or manually activated from outside the building. A heater and heat exchanger have also been installed so that the system can be operated in cold or hot weather.

Battery Controller Software

A separate programmable logic controller (PLC) monitors and controls each battery module. Each PLC has 2 K of user memory and is capable of data acquisition through a full-duplex RS232C serial port. During FY96, calibration of the voltage and current sensors for the modules and the final logic and data acquisition software were completed. The PLCs will monitor module voltage, stack current, pump motor currents, and electrolyte levels in the module reservoirs. The PLCs will compare the measured parameters with preset limits to determine if the battery modules are performing properly. If the measured parameters fall outside the preset norms, the PLCs will adjust variables, e.g., pump speed, to compensate. If the measured parameters cannot be modified, the PLCs will generate either a "FAULT" or a "SHUTDOWN" condition and proceed to turn off the system. A "FAULT" condition causes the battery to be disconnected from the PCS. A "SHUTDOWN" condition gives the same result as the "FAULT" condition, but the entire system, including pumps, will be shut down.

An additional PLC will coordinate the overall operation and safety of the system. This controller will monitor system parameters such as electrolyte temperatures, bromine and hydrogen concentrations inside the building, building temperature, ambient temperature, peripheral current, and seismic activity. If a condition that is potentially hazardous to the system or to its surroundings is sensed by the monitoring system, the controller will completely shut down the system. Conditions that would result in a complete shutdown of the system include an electrolyte or coolant leak, an earthquake, or high levels of bromine.

The performance of the system is monitored by a computer system with software running under the Microsoft Windows environment. The PLCs monitoring the battery system send the data over RS232C serial lines to the computer. Various screens display the information collected by the monitoring PLCs. The information includes parameters such as module and system voltage and current, electrolyte pump speeds, temperatures, seismic activity, hydrogen and bromine gas concentrations, and parasitic load conditions. The information is saved for retrieval at a later time and can be presented in either tabular or graphical format.

The system software is programmed to allow the operator to manually change the speed of the various pumps as well as to generate a "MANUAL SHUTDOWN" of the system. If the system is shut down or halted either manually or by the PLCs, the software will notify key personnel via personal pagers contacted through a modem connected to the computer.

100-kWh Battery Characterization

Interference caused by noise from the PCS had previously made voltage readings by the personal computer inconsistent. During FY96, methods were developed to electrically isolate the battery. The PLCs are now able to consistently read battery voltages without being affected by the noise from the PCS.

Erratic currents through individual battery stacks have caused some problems. These currents appeared to be caused by the inability to strip the batteries following discharge. Because of this, the batteries were not all at the same state of charge (SOC) at the beginning of each cycle, and individual stack currents became more inconsistent on each subsequent cycle. Strip resistors for each of the three battery modules, along with electrical contactors to switch from the PCS to the resistor banks, have been installed inside the 100-kWh building to address this problem.

Safety-protection features have been incorporated into the system. The gas-sensor monitor has been calibrated and is operational.

The fault and shutdown conditions listed in Table 3-2 have been used to verify that the protection features of the zinc/bromine battery are functioning. Each event is documented in a computer-generated report and is also backed up on the hard disk of the Battery Monitoring personal computer (PC). Confirmation of the protective functions is complete.

Reaching low-voltage cutoff was originally considered a fault condition. Now, rather than treating low-voltage cutoff as a fault condition, the response is to open the DC contactor and connect the batteries to resistor banks so that the batteries can be stripped. Before the batteries are stripped, all battery modules must be within a specified voltage window.

Table 3-3 lists the response sequences that result from fault and shutdown conditions. The fault response sequence occurs after minor faults and the shutdown response sequence after critical faults.

The shutdown response for a fire within the building has also been modified. If there is a fire, all power is removed from the system and a warning bell is activated.

The final ladder logic has been completed. Data are being entered into the PC, and amp-hours, watt-hours and SOCs are being calculated. Progressively longer cycles are being performed on the battery system to verify SOC calculations. The electrolyte flow rates that will give optimized battery performance are being examined.

During FY96, unexplained shutdowns of the inverter were identified, and a new controller board is scheduled to be installed in December 1998. Safety prequalification testing of the new controller board was completed. Optimization of battery performance will commence once the new controller board is installed.

Also during FY96, the electronics and software to run the battery were tested. Testing was initiated on a three-battery configuration. These stacks were some of the first few built and did not meet quality specifications. However, they did perform very consistently during the 18 cycles for which they were tested, with the final cycle giving coulombic efficiency of 79.6%, voltaic efficiency of 87.7%, and energy efficiency of 69.9%.

Table 3-2. Fault and Shutdown Conditions for 100-kWh Battery

Fault Conditions	Shutdown Conditions
Overvoltage in Charge	Loss of 120-V, 30-A Supply
Overcurrent in Charge	Bromine Detection
Door Open	Accelerometer Activation
Hydrogen Detection	Leak Detection
Above Maximum Temperature	Level Sensors Off
Below Minimum Temperature	Fire

Table 3-3. Fault and Shutdown Responses for 100-kWh Battery

	Fault Response		Shutdown Response
1	Pump motors remain on.	1	Pump motors are turned off.
2	DC contactor opens.	2	Horn sounds.
3	Alarm light turns on.	3	Alarm light turns on.
4	The MGTF Test Manager is paged.	4	Both louvers close.
5	Fault indicator to PCS opens.	5	Scrubber turns on.
6	Alarm screen appears on the battery-monitoring PC.	6	The MGTF Test Manager is paged.
7	Alarm horn on the battery-monitoring PC sounds.	7	DC contactor opens.
8	Event is recorded to the battery-monitoring PC hard disk.	8	Fault indicator to PCS opens.
9	Event is sent to the printer.	9	Fault indicator to PG&E opens.
10	All subsequent operator actions are recorded to the battery-monitoring PC hard disk.	10	Alarm screen appears on the battery-monitoring PC.
11	All subsequent operator actions are sent to the printer.	11	Alarm horn on the battery-monitoring PC sounds.
		12	Event is recorded to the battery-monitoring PC hard disk.
		13	Event is sent to the printer.
		14	All subsequent operator actions are recorded to the battery-monitoring PC hard disk.
		15	All subsequent operator actions are sent to the printer.
		16	Heat exchanger turns off.

Minor changes were made in the software and ladder logic to enable the battery to run unmanned cycles. Strip resistors have been added to the system to allow unmanned stripping of the battery. Once the new controller board is installed in December 1998 (with new software), a major portion of stripping function will be performed by the PCS.

4. Component Research and Development – Technology Evaluation/Applied Research at SNL

Introduction

As part of its technical mission in support of the ESS Program, SNL performs in-house applied research and battery evaluation tasks. These tasks are performed by utilizing specialized and unique facilities and capabilities established at SNL over the many years of program activities in all battery technologies.

Evaluation of VRLA and advanced batteries is being performed in the extensive battery testing labs at SNL. These independent, objective tests using computer-controlled testers capable of simulating application-specific test regimes provide critical data for the assessment of the status and probable success of these technologies. Current tasks include conclusion of the development of a safety fuse for sodium/sulfur and other high-temperature batteries. This development of patentable fuse materials builds on SNL's extensive technical capabilities in high-temperature cells and materials.

VRLA and Lead-Acid SLI Evaluation at SNL

PV Battery Cycle-Life Evaluation at SNL

The ESS Program has been working in coordination with the Sandia Photovoltaic System Components Department at SNL to characterize the life and performance of commercially available batteries for use in renewable systems. Several battery types are being evaluated including starting, lighting, and ignition (SLI); deep-cycling flooded; and types using VRLA technologies. To ensure that the batteries under test represented components that are available to PV systems integrators, most of the batteries under test were purchased by Sandia through the same distribution system that provides batteries to PV systems integrators. Other batteries, such as the SLI battery and new VRLA gel technology batteries, were acquired from off-shore factories or direct from U.S. manufacturers because these batteries are unique and not generally available to PV systems integrators.

The purpose of the testing being conducted by the Photovoltaic System Components Department at the PV battery test facility (with consulting support provided by the ESS Program) is to determine potential PV applications that may be serviced with the GNB 12-5000X 12-V battery, which is ABSOLYTE IIP technology. Extensive testing of the GNB 12-5000X battery is also under way at the Florida Solar Energy Center (FSEC). The tests are intended to characterize the operation of the battery under abusive conditions to determine the range of operations that this battery can tolerate and still perform satisfactorily. Testing at FSEC is being performed under a contract managed by the Photovoltaic System Applications Department.

GNB 12-5000X 12-V Testing

PV battery cycle-life tests are being conducted on GNB 12-5000X 12-V batteries. A dozen batteries were received in April 1996; two of the twelve batteries were put on test immediately. The capacities of these batteries at this time were 99 and 106 Ah at a C/35 (2.86-A) rate. After 5 mo of sitting at room temperature, battery capacity on four other batteries was measured at 69 to 74 Ah at a C/20 rate (5 A). All initial battery capacity measurements were made after a 12-hr boost charge at 14.1 V. The battery capacity test results after 5 mo of storage indicated that a 26 to 30% stand loss had occurred.

Preliminary test results showed that the initial boost charge for 12 hr at 14.1 V left the battery at a 30% deficit charge condition. Also, if the boost-charge amp-hours are subtracted from the initial capacity measurement, the capacity of the battery after 5 mo of storage would only be 51% of its initial capacity as measured when the batteries were first received. The boost charge to the as-received batteries added 8 Ah.

The following recovery procedure was initiated:

1. Boost charge the batteries at 2.35 vpc until the charge current levels out for 3 hr.

2. Boost charge the batteries for another 12 hr at 2.35 vpc.

A recharge to 14.1 V and a 36-hr boost/float charge at 14.1 V was sufficient to recover battery capacity as defined in Steps 1 and 2 above. After 36 hr, the current had just begun to level out at 0.51 A (C/400), which indicated that another 12 hr of charge would be required. The additional 12 hr of charge was not implemented because of uncertainty over how long Step 1 would require and because a deep cycle also helps to recover more battery capacity. Actual capacity measurements show that the measured battery capacity (173 Ah) increased above the amount recharged in the previous cycle (168 Ah). This supports the theory that the combination of extended boost/float charge and deep cycling recovers more capacity.

As the data in Figure 4-1 demonstrate, the standard 12-hr boost charge may not be adequate to prepare the battery for the PV Battery Cycle-Life Test Procedure. (Note: The horizontal scale is not linear. This is to make it easier to mark the duration of each event, i.e., charge or discharge, from the beginning until the end of the event.) It is necessary to look at the charge current to determine if the battery is at full charge. The data indicate that an end-of-charge current of 0.250 A (C/400) should be required before the initial capacity measurement is made. This may require as much as 24 to 48 hr on boost/float charge.

GNB ABSOLYTE II and IIP and Yuasa-Exide Testing

The reliability of VRLA batteries, both those developed by GNB for SNL and those commercialized by others, has been seriously questioned. Utilities and telecommunications users of VRLA-based systems have experienced field failures and reliability problems. SNL is attempting to address these issues with industry involvement to better understand the problems, degradation mechanism(s), and possible solutions. A critical component of this activity is the continued laboratory evaluation of VRLA batteries at SNL. Controlled laboratory tests are the best method to determine capacity degradation rates and mechanisms. While field tests will exhibit the same problems, there are almost always too many uncontrolled variables to allow an understanding of the cause-and-effect relationships.

Status

Testing of contract deliverables from the GNB VRLA development contract continued at SNL during FY96. Two 18-V batteries, an ABSOLYTE II and an ABSOLYTE IIP, have undergone extensive testing during the year. In addition, a VRLA battery from Yuasa-Exide was tested to characterize the technology. The rated capacity of the ABSOLYTE II is 1040 Ah at the C/8 discharge rate. The rated capacity of the ABSOLYTE IIP is 1200 Ah at the C/8 discharge rate. The rated capacity of the Yuasa-Exide battery is 110 Ah at the C/8 discharge rate. This report contains test results from these three units. All three batteries will remain on test until the units have lost 20% of their

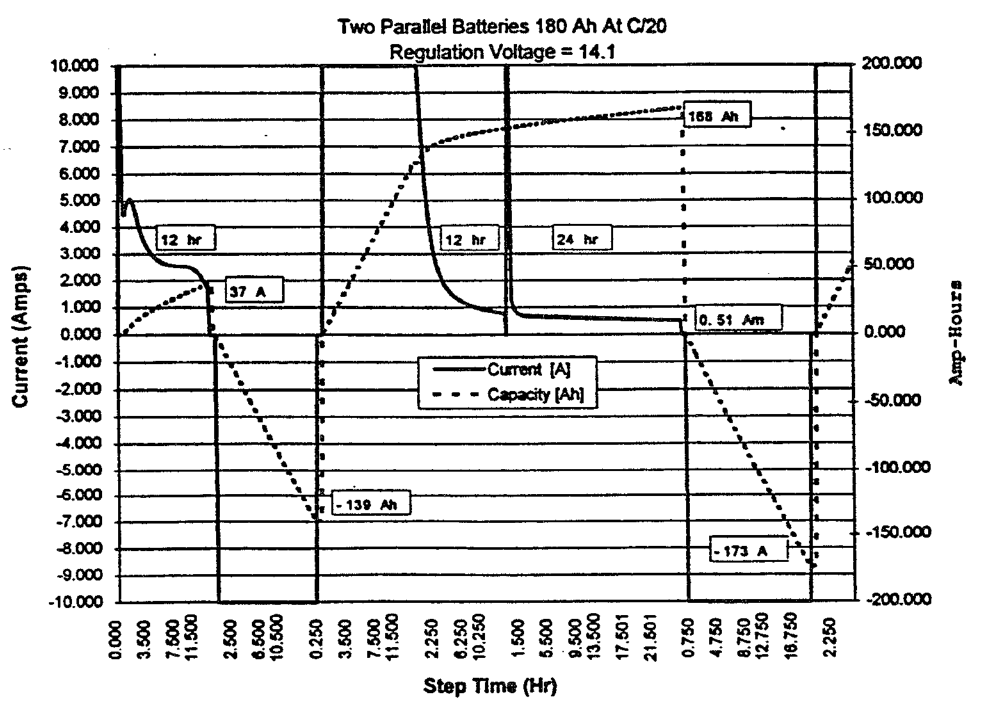


Figure 4-1. **GNB 12-5000X Boost Charge.**

capacity. The data generated in these tests will also be used in the VRLA Reliability Improvement task.

ABSOLYTE IIP Testing

Frequency regulation and spinning-reserve tests were continued on the ABSOLYTE IIP in FY96. As discussed in the FY95 annual report, such tests were performed to evaluate the capability of the ABSOLYTE IIP to meet a defined frequency regulation/spinning-reserve UES cycle. For specific details of the UES cycle used for testing the ABSOLYTE IIP, as well as background information of these tests, please refer to Section 3 of the Utility Battery Storage (UBS) Program Report for FY95.

Two full UES cycles were accomplished on an ABSOLYTE IIP module in the first quarter. Results of the second cycle (Cycle 141) are shown in Figure 4-2 and Table 4-1. Figure 4-2 shows plots of the voltage, current, and power responses of the ABSOLYTE IIP for all three frequency regulation sessions, which were separated by intermediate charges (defined in Table 4-2). The spinning-reserve and refresh charge parts of the cycle are not shown on these plots because their scales are quite different from the frequency regulation scale. Note on the voltage plot that almost all the larger positive peaks, as well as the medium peaks at the beginning of each session, are limited. This was caused by the battery reaching the preset tester voltage limit of 21.15 V (2.35 vpc) while the battery was at a higher SOC. The preset voltage limit was set to protect the battery from excessive gassing during the frequency regulation operation. Also note that the last five larger peaks of the first frequency regulation session did not reach the voltage limit.

Table 4-1 gives summary information for the three frequency regulation sessions. As indicated in the table, each session started with the ABSOLYTE IIP at 90% SOC and ended when the battery reached approximately 70% SOC. SOC measurements were based on accumulated amp-hours removed (AhOut) and accumulated amp-hours returned (AhIn). Furthermore, SOC was recalculated as shown below each time either the AhOut or AhIn counter was updated, which was programmed to occur a few seconds before and a few seconds after each power level change. The rated capacity used for the given formula was 1200 Ah.

As shown in Table 4-1, 23 160-min subcycles were accomplished in a 61-hr period during the first frequency regulation session, whereas 19 160-min subcycles were accomplished in approximately 51 hr during the second and third sessions. With the battery at approximately 70% SOC, a spinning-reserve discharge test immediately followed the third frequency regulation session. For this part of the UES cycle, the ABSOLYTE IIP was discharged at a constant power rate of 11.38 kW for 16.7 min, followed by a linear ramp from 11.38 kW to 0 kW over a period of another 16.7 min. The spinning-reserve test caused the battery SOC to drop an additional 24% from the 70% point. Then, with the battery at approximately 46% SOC, a refresh charge (see Table 4-2) was applied to bring the battery back up to 100% SOC.

Temperatures at various locations on the ABSOLYTE IIP battery were also measured and recorded during the UES cycle tests. The data showed that temperatures were fairly stable from the start to the finish for each frequency regulation session (change in temperature <1°C).

Following this UES cycle (Cycle 141), the ABSOLYTE IIP sat at open circuit for a few weeks during SNL's Christmas shutdown. When SNL operations resumed, at the beginning of the second quarter, three C/8 (150-A) constant-current capacity tests (1.75 vpc end-of-discharge voltage) were performed to determine the current SOC and also to evaluate the effect of the preceding UES cycles on measured capacities. The normal overcharge (E) regime specified in Table 4-2 was used to recharge the ABSOLYTE IIP prior to the second and third discharges, while the refresh charge of the last UES cycle preceded the first C/8 test. As shown in Table 4-2, the two regimes are nearly identical, the difference being the cutoff parameter of the 24-A constant-current step, but both regimes produce essentially the same amount of overcharge (7%). For the first C/8 discharge to 1.75 vpc (Cycle 142), 1207 Ah was measured. For the second C/8 discharge (Cycle 143), 1274 Ah was measured. For the third (Cycle 144), 1299 Ah was measured. Note that each of these measurements has been normalized to a start-of-discharge temperature of 77°F using a compensation factor of 3 Ah/°F. These measurements are comparable to those of identical cycles (Cycles 121 to 128) that were performed just before the start of frequency regulation and spinning-reserve testing.

Following these capacity tests, at the request of SNL's PV System Applications Department (Department 6218), several tests were performed in order to characterize the ABSOLYTE IIP for a specific renewable application. Department 6218 has been asked by the Arizona Public Service Company (APS) to assist in the optimization of a hybrid power system that uses ABSOLYTE IIP cells and is located on Carol Spring Mountain, Arizona. The characterizations provided Department 6218 with the details it needed to make the appropriate recommendations.

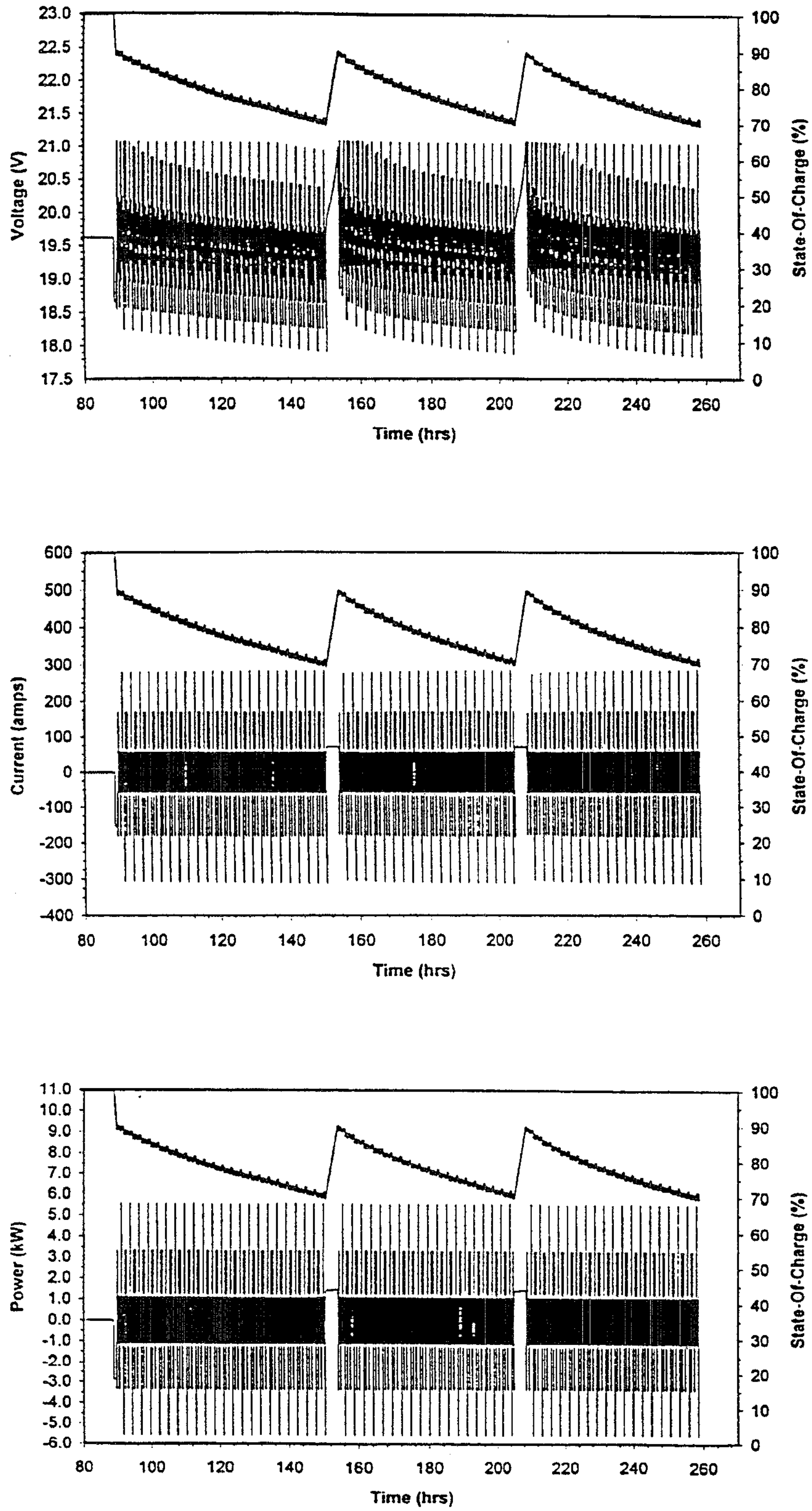


Figure 4-2. Voltage, Current, and Power Responses of the ABSOLYTE IIP for Three Consecutive Frequency Regulation Sessions of a UES Cycle (Cycle 141).

Table 4-1. Summary of Frequency Regulation Data of a UES Cycle on the ABSOLYTE IIP (Cycle 141)

Session #	SOC at Start of Session (%)	No. of Subcycles Completed	Length of Session (hr)	Accumulated Ah Removed During Session (AhOut)	Accumulated Ah Returned During Session (AhIn)	SOC at End of Session (%)
1	90.0	23	60.9	2740	2496	69.5
2	90.0	19	50.9	2294	2053	69.8
3	90.0	19	50.2	2260	2017	69.6

SOC = state of charge

Table 4-2. Regimes Used for Recharging the ABSOLYTE II and IIP

Regime Name	Regime Specifications	Required Time to Complete Regime from Fully Discharged (C/8) Condition	
		ABSOLYTE II	ABSOLYTE IIP
Normal Overcharge (E)	CI (300 A) until 2.40 vpc, CV (2.40 vpc) until 24 A, CI (24 A) until 7% overcharge, OC for 8 hr	7 hr	16 hr
Boost Charge (B)	CI (300 A) until 2.35 vpc, CV (2.35 vpc) until 20.8 A, CI (20.8 A) for 8 hr, CV (2.35 vpc) for 48 hr	64 hr	64 hr
Intermediate Charge (B)	CI (72 A) until 2.35 vpc, CV (2.35 vpc) until 90% SOC, OC for 5 min	--	3.4 hr
Refresh Charge	CI (300 A) until 2.40 vpc, CV (2.40 vpc) until 24 A, CI (24 A) for 2 hr, OC for 8 hr	--	16.5 hr

CI = constant current CV = constant voltage OC = open circuit
vpc = volts per cell SOC = state of charge

Each specified test is described below. Specifically, the APS system uses a series string of 96 Type 100A-51 cells. Since the SNL test battery uses nine Type 100A-25 cells, the power levels of each test were scaled down. The 281-W discharge rate was scaled down from a system load of 6 kW, while the 1125-W charge rate was scaled down from a charge rate of 24 kW. The test regimes follow:

- Constant-Power Discharge (CPD) Test: Discharge at the 281-W rate from a full SOC to an end-of-discharge voltage of 1.75 vpc (100% DOD).
- Recharge Time (RT) Test: Following a constant-power discharge at the 281-W rate to an end-of-discharge voltage of 2.03 vpc, recharge at the 1125-W constant-power rate to 2.35 vpc, and

then clamp at the 2.35-vpc level until 7% overcharge is reached.

- Cycling Test: Beginning at full SOC, repetitiously discharge at the 281-W rate to an end-of-discharge voltage of 2.03 vpc, and then recharge at the 1125-W rate to 2.35 vpc and clamp at the 2.35-vpc level for 2 hr.
- Discharge Capacity Test: Discharge the battery at the same rate as the cycling tests (281-W constant power) to 100% DOD (1.75 vpc), and then recharge at the 1125-W rate to 2.35 vpc. Clamp at the 2.35-vpc level for 2 hr for the first test, then run a second test and clamp for 12 hr.

The objective of the first test, the CPD test, was to determine the SOC of the ABSOLYTE IIP at the 2.03-vpc level. The 2.03-vpc level was the set point at which the generators would turn on in order to recharge the hybrid system's battery. The concern was whether an appropriate amount of the battery capacity was being used when the system was at this set point. At the 281-W constant-power rate, the ABSOLYTE IIP yielded 1625 Ah of total available capacity and took approximately 105 hr to fully discharge. The battery reached the 2.03-vpc level 52.5 hr from the start of the discharge, at which point 785 Ah were removed. This equates to 48.3% removal of the total available capacity.

One other piece of information that was of particular interest from this first test was the drop in voltage at the start of discharge for the 281-W rate (open-circuit to closed-circuit). The open-circuit voltage just prior to the start of discharge was measured at 2.18 vpc. The closed-circuit voltage just after the start of discharge was measured at 2.13 vpc. Therefore, the voltage drop was 0.05 vpc.

The objective of the second test, the RT test, was to determine the length of time required to recharge the battery at the 1125-W rate to a charge voltage of 2.35 vpc and also to an overcharge of 7% from an end-of-discharge voltage of 2.03 vpc (281-W discharge rate). Results of this test showed that it took 11.1 hr for the ABSOLYTE IIP battery to reach the 2.35-vpc charge voltage from the SOC. At this point 82.7% of the capacity removed during the prior discharge was put back into the battery. Two hours later, 94.1% was returned. Finally, after an additional 7.1 hr at the 2.35-vpc charge voltage level, 7% overcharge was reached. Therefore, the total required time to reach 7% overcharge (full SOC) was 20.2 hr from the state of charge.

The objective of the cycling tests was to determine the discharge capacity stability of the ABSOLYTE IIP when repetitiously cycled as specified in the description of a cycling test given above. Results of this study are shown in Figure 4-3 and Table 4-3. Figure 4-3 shows a

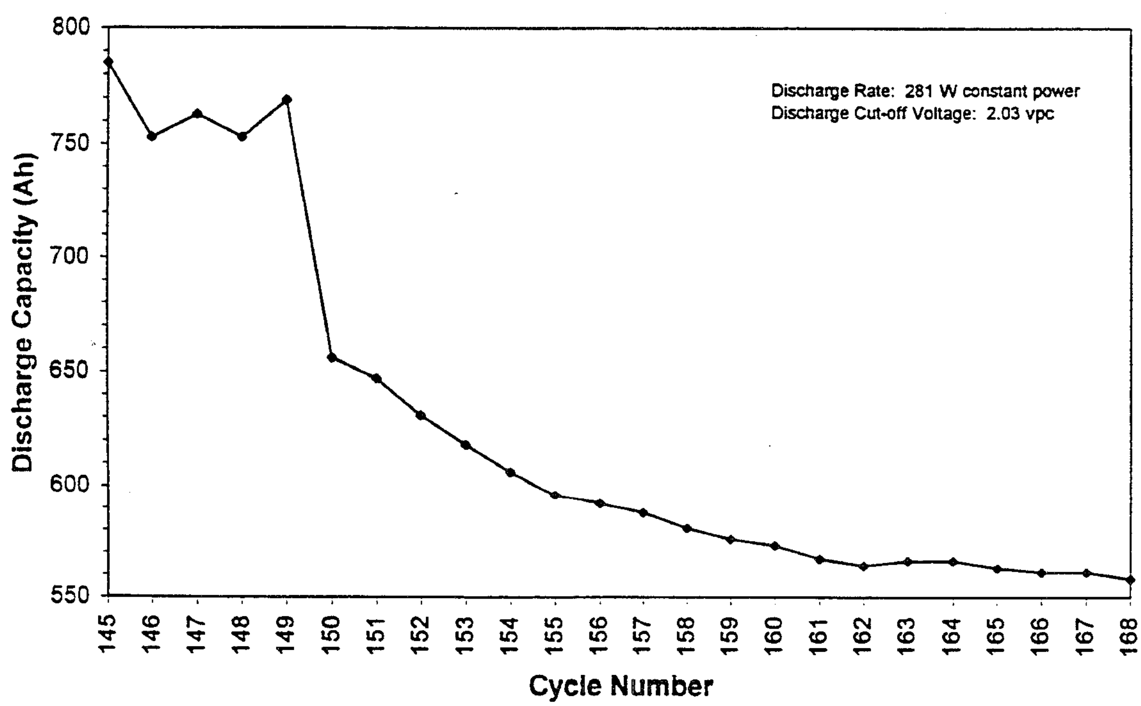


Figure 4-3. ABSOLYTE IIP Discharge Capacity Loss Rate for a Specific Renewable Application Recharge Regime: 1125-W Constant Power to 2.35 vpc, Followed by 2-hr Clamp at 2.35 vpc.

Table 4-3. ABSOLYTE IIP Discharge Capacity Measurements for a Specific Renewable Application Recharge Regime

	Capacity Removed at 2.03 vpc	
Cycle #	in Ah	in % of rated capacity to 2.03 vpc, 785 Ah
145	785	100.0
146	753	95.9
147	763	97.2
148	753	95.9
149	769	98.0
150	656	83.6
151	647	82.4
152	631	80.4
153	618	78.7
154	606	77.2
155	596	75.9
156	592	75.4
157	588	74.9
158	581	74.0
159	576	73.4
160	573	73.0
161	567	72.2
162	564	71.8
163	566	72.1
164	566	72.1
165	563	71.7
166	561	71.5
167	561	71.5
168	558	71.1

plot of all measured discharge capacities to the 2.03-vpc cutoff, while Table 4-3 gives the same information for the individual cycles, but in tabular form for reference. It should be noted that for Cycles 145 through 148 the recharge regime used was not the same as that specified above for cycling tests, but was instead a regime designed to accomplish full recharge (7% overcharge). Measured discharge capacities from these cycles were included to show a representative baseline of typical performance for a battery recharged using the manufacturer's specifications, which are shown in Table 4-2 as the normal overcharge (E) regime. Table 4-3 also shows each measured capacity divided by the rated capacity, 785 Ah, indicating inefficiency of recharge for the successive cycles.

The larger decrease from Cycle 149 to 150, seen in Figure 4-3, undoubtedly results from the change from one recharge profile to the other, and represents the degree of undercharging caused by the partial recharge regime. However, the gradual decrease from Cycle 150 forward was attributed by GNB to a continual buildup of sulfation on the plates. Because the prior recharge was not enough to completely clear the plates, each time the battery was discharged more sulfation accumulated. Accumulation of lead sulfate in conjunction with the loss of sulfate ions from the electrolyte caused an increase in internal resistance and consequently a loss of battery rechargeability.

The objective of the first discharge capacity test (Cycle 169) with the 2-hr clamp was to determine the discharge capacity following the cycling test with the 2-hr clamp at 2.35 vpc. In order to determine the discharge capacity following this regime, the battery was discharged at the same rate as during the cycling tests (281-W constant power), but the discharge was to 100% DOD (1.75 vpc). The comparison of this capacity to the cycling test capacity indicates how close the cycling test actually gets the battery to a full SOC. The measured capacity for this test was 1384 Ah, which is 86% of the available capacity when the battery starts at a full SOC. As mentioned previously, the ABSOLYTE IIP yielded 1625 Ah for the 281-W constant-power rate.

The purpose of the second discharge capacity test (Cycle 170) was to determine the total available capacity of the battery following the same charge regime, but instead of clamping for 2 hr, the charge voltage was clamped for 12 hr. The result was that the available capacity is more than that for the first discharge capacity test, since the clamp was 10 hr longer. The measured capacity was 1538 Ah, which is 95% of the 1625-Ah measurement.

Upon completion of the four sets of tests performed for SNL's PV System Applications Department, the battery was placed on a life-cycle testing regime. By the end of FY96, a total of 33 life cycles at the C/8 discharge rate had been performed (Cycles 171-203). Figure 4-4 is a plot of Ah removed and Ah returned for these cycles. The charge regime used on Cycle 171 was the normal overcharge (E) shown in Table 4-2. During the next 21 cycles (Cycles 172-192), the charging regime was modified to improve compatibility between the tester and battery and to try to improve the charge acceptance of the battery. Charge 1 was changed to return the Ah that were removed during discharge. Also, a 5-min wait period between Charge 1 and Charge 2 was added. This was later replaced with a cool-down period to allow the battery temperature to cool to less than 40°C. A third wait period was added before Charge 3, which finished putting in the 7% overcharge. The final charge regime used for Cycles 193-203 is called the normal overcharge (F) and is discussed below.

- 5-min wait period after discharge.
- CI (300 A) until 21.6 V (2.40 vpc) or Ah removed are returned.
- Wait period to allow battery to cool to <40°C.
- CV (21.6 V/2.40 vpc) until 24 A or 7% overcharge.
- 3-min wait period.
- CI (24 A) until (23.85 V/2.65 vpc) or 7% overcharge.

As can be seen in Figure 4-4, there was an improvement in battery capacity from Cycle 171 to Cycle 180, but from Cycle 180 to Cycle 203 a gradual decline was measured. Life-cycle testing will continue, and attempts will be made to identify the cause of the decline in capacity.

ABSOLYTE II Testing

Testing of the ABSOLYTE II deliverable continued to be performed after the start of testing of the ABSOLYTE IIP. During the first quarter, the ABSOLYTE II was subjected to several series of constant-current discharge tests. These were done to characterize the battery at the C/2, C/8, and C/20 rates to 100% DOD, and also to compare performance of the ABSOLYTE II design with that of the enhanced ABSOLYTE IIP design at the same discharge rates. As discussed in the UBS Program Report for FY95, the objective of the performance comparison was to evalu-

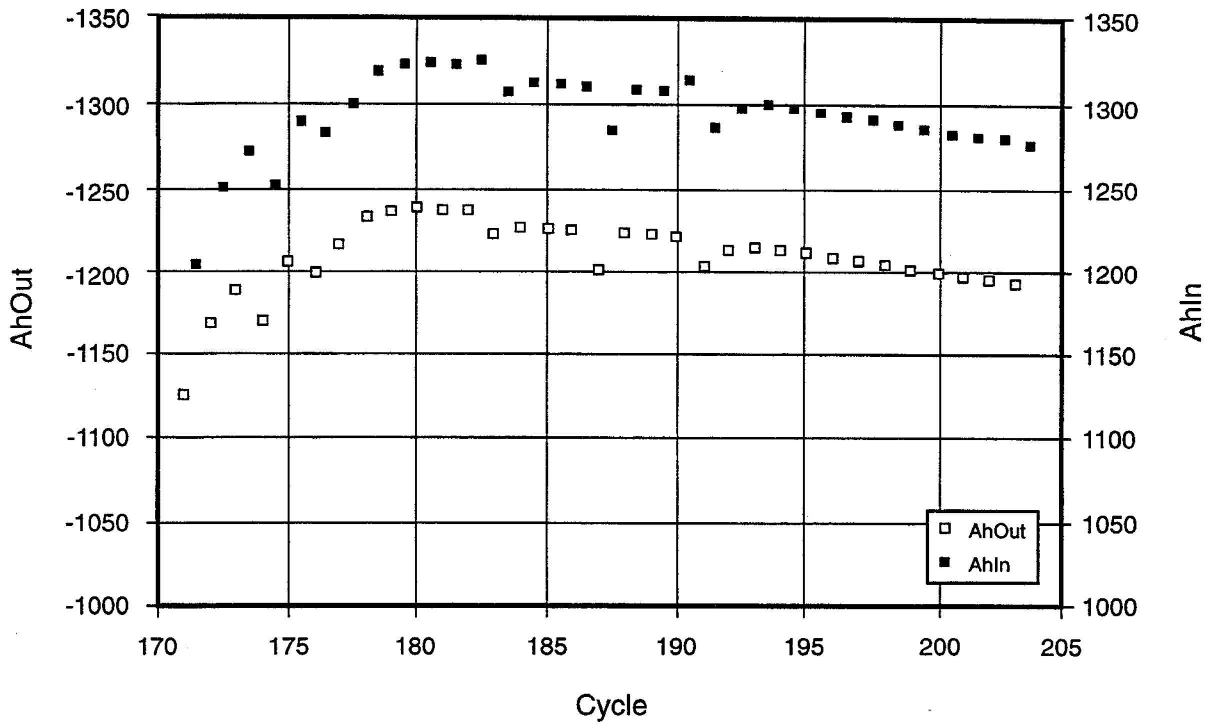


Figure 4-4. **Plot of Ah Removed (AhOut) and Ah Returned (AhIn) for Cycles 171-203 for ABSOLYTE IIP.**

ate improvements in performance using the ABSOLYTE IIP design over that using the ABSOLYTE II design.

Before beginning these series of constant-current discharge tests, the ABSOLYTE II was given, as part of Cycle 52, a boost charge (B) as defined in Table 4-2. This was to ensure that the plates were cleared of sulfation and that the battery was completely charged prior to further testing. The boost charge (B) regime was the same as that used for the ABSOLYTE IIP (described in Table 4-3 of the UBS Program Report for FY95), except that the constant-current level was scaled down from the 24 A used for the ABSOLYTE IIP to 20.8 A. Note in Table 4-2 that both regimes required the same amount of time to accomplish, 64 hr.

Table 4-4 shows measured capacity results from the C/2 (425 A) constant-current discharge tests of the ABSOLYTE II battery. The cutoff voltage was 1.75 vpc. The normal overcharge (E) regime was used for recharging prior to each discharge. Also shown in Table 4-4 are results of identical tests performed on the ABSOLYTE IIP, also using the normal overcharge (E) regime for recharging. Capacity measurements for each battery have been averaged to make comparison easier. At the C/2 rate, the ABSOLYTE IIP delivered 3.6% higher capacity.

Table 4-5 shows a similar comparison of measurements from the C/8 (150-A) discharge tests. The cutoff voltage for these tests was also 1.75 vpc. As shown in the table, at this rate each battery delivered about the same capacity.

Table 4-6 gives the same comparison for the C/20 (68-A) tests. Again, the cutoff voltage for these tests was 1.75 vpc. Each battery again delivered approximately the same capacity.

These tests show some improvement in capacity at higher discharge rates from one design to the other. In addition, evidence of increasing capacity for the ABSOLYTE IIP design did begin to appear after it underwent approximately 10 deep-discharge cycles immediately following a boost charge (Cycle 120). Starting at Cycle 121, which was a C/8 constant-current discharge test to an end-of-discharge voltage of 1.75 vpc, followed by a normal overcharge (E) recharge, capacity measurements jumped from 1066 Ah (prior to the boost charge) to 1238 Ah. On the third additional cycle conducted as stated above, Cycle 124, the measured capacity peaked at approximately 1300 Ah. Furthermore, following the UES cycle testing that was discussed earlier in this report, more of the same C/8 discharge/normal overcharge (E) tests were performed

Table 4-4. Comparison of ABSOLYTE II and IIP C/2 (425-A) Discharge Capacities when Using Normal Overcharge (E) Recharge Regime

ABSOLYTE II		ABSOLYTE IIP	
Cycle #	Measured Capacity (Ah) Normalized to 77°F	Cycle #	Measured Capacity (Ah) Normalized to 77°F
60	875	95	903
61	842	96	879
62	850	97	886
63	844	98	882
	853 avg. (15.2)	99	881
		100	880
		101	880
		102	877
			884 avg. (8.3)

Note: The numbers in parentheses represent the standard deviation.

Table 4-5. Comparison of ABSOLYTE II and IIP C/8 (150-A) Discharge Capacities when Using Normal Overcharge (E) Recharge Regime

ABSOLYTE II		ABSOLYTE IIP	
Cycle #	Measured Capacity (Ah) Normalized to 77°F	Cycle #	Measured Capacity (Ah) Normalized to 77°F
70	1199	109	1226
74	1200	110	1224
75	1172	111	1212
76	1215	112	1206
91	1226	113	1203
92	1208	114	1199
93	1198	115	1195
	1203 avg. (16.9)		1209 avg. (12.0)

Note: The numbers in parentheses represent the standard deviation.

Table 4-6. Comparison of ABSOLYTE II and IIP C/20 (68-A) Discharge Capacities when Using Normal Overcharge (E) Recharge Regime

ABSOLYTE II		ABSOLYTE IIP	
Cycle #	Measured Capacity (Ah) Normalized to 77°F	Cycle #	Measured Capacity (Ah) Normalized to 77°F
65	1454	104	1452
66	1449	105	1420
67	1447	106	1451
68	1401	107	1418
	1438 avg. (25.0)		1435 avg. (19.1)

Note: The numbers in parentheses represent the standard deviation.

(Cycles 142 to 144). The measured capacity again peaked at approximately 1300 Ah. Assuming that available capacity of the ABSOLYTE II does not increase from 1200 Ah further along in its life, the ABSOLYTE IIP now appears to be providing an 8.3% improvement in capacity at the 8-hr constant-current rate.

GNB later explained that the density and weight of the positive active material paste of the ABSOLYTE IIP design were increased from their levels in the ABSOLYTE II design. Although it is logical to assume that this would provide an increase in capacity, initially this was not the case because the increased density restricted diffusion of electrolyte. However, as the battery was cycled, the active material became somewhat more porous, allowing for better diffusion of the electrolyte and resulting in the increased capacity measurements. Additionally, longer life under cyclic conditions can be expected. Unfortunately, it takes approximately 125 deep cycles to access the extra available capacity of the ABSOLYTE IIP. Also, during this period the required time to fully recharge the ABSOLYTE IIP using the GNB-prescribed normal overcharge (E) regime is approximately 9 hr longer than that for the ABSOLYTE II, as is shown in Table 4-2.

All measured capacities of the ABSOLYTE II cycles shown in Tables 4-4, 4-5, and 4-6 have been plotted on the Peukert Plot of Figure 4-5. Note that all capacity values for each rate are overlapped to illustrate capacity stability.

Testing of the ABSOLYTE II continued into the second quarter of this fiscal year. During the second quarter, a special study was initiated to determine the effect on discharge capacity of the ABSOLYTE II after float charging at specific constant-voltage levels. The purpose of the study was to provide guidance to NMSU in the setup of renewable systems for the U.S. Coast Guard that utilize the ABSOLYTE technology for energy storage.

Specifically, each test consisted of a float charge at either 2.15 vpc, 2.18 vpc, or 2.21 vpc, followed by a C/8 (150-A) constant-current discharge to an end-of-discharge voltage of 1.75 vpc. Float charges for each test were accomplished by first applying an in-rush current of 100 A to the battery until the desired float voltage was reached, at which time the voltage was clamped for the remainder of a 72-hr period. However, some of the cycles were interrupted before the 72-hr mark. The 2.15-vpc test was repeated six times, while each of the 2.18-vpc and 2.21-vpc tests was repeated three times.

Results of all 12 tests are summarized in Table 4-7. Included in the table are the exact times that the ABSOLYTE II spent at each of the two recharge steps for each cycle, as well as the measured capacity following each float charge. The inefficiency of float charging at each of the three levels is represented in the last column as percentage of nominally measured capacity (at 1200 Ah) for each discharge capacity measurement.

In summary, the average available capacity of the ABSOLYTE II after float charging at the 2.15-vpc level

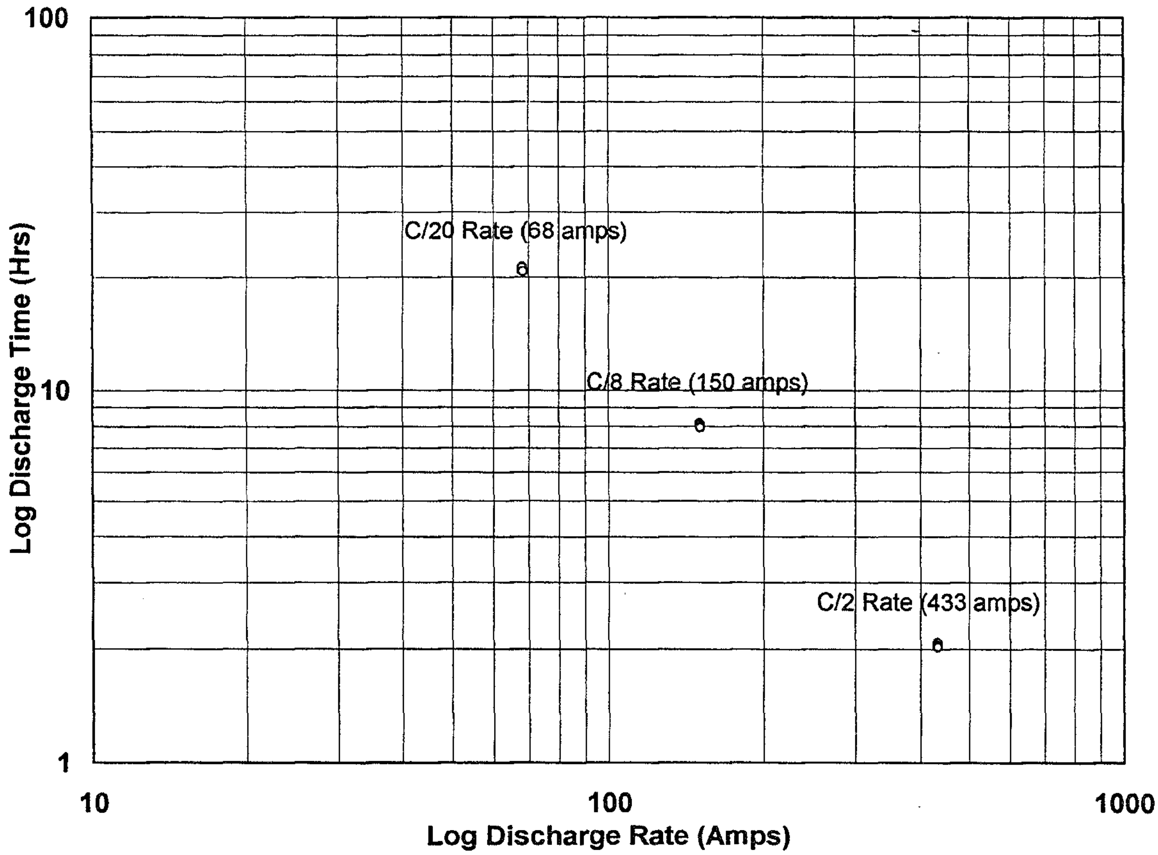


Figure 4-5. Peukert Plot of ABSOLYTE II Constant-Current Discharges.

Table 4-7. Effect of Various Constant-Voltage Float Levels on the ABSOLYTE II

Charge Cycle #	Charge Voltage Level (vpc)	Required Time to Reach Charge Voltage (hr)	Length of Time Charge Voltage was Held (hr)	Affected Discharge Cycle #	Affected Discharge Capacity (Ah), Normalized to 77°F	Percentage of Nominal Capacity to 1.75 vpc (%)
79	2.15	2.7	64.2	80	861	71.8
80	2.15	2.7	69.3	81	877	73.1
81	2.15	2.9	69.1	82	862	71.8
82	2.15	2.5	69.5	83	856	71.3
83	2.15	2.5	69.5	84	865	72.1
84	2.15	2.5	68.2	85	876	73.0
76	2.18	4.7	19.3	77	966	80.5
77	2.18	4.8	67.2	78	1022	85.2
78	2.18	3.9	68.1	79	1018	84.8
85	2.21	5.4	66.6	86	1123	93.6
86	2.21	5.1	66.9	87	1106	92.2
87	2.21	5.4	66.6	88	1041	86.8

is approximately 72%. The average available capacity after float charging at the 2.18-vpc level is approximately 84%. The average available capacity after float charging at the 2.21-vpc level is approximately 91%. This trend suggests that float charging at the next 0.03-vpc increment (2.25-vpc) would provide for approximately 100% recharging, and 2.25 vpc is the lowest recommended float voltage specified in the operating manual for the ABSOLYTE II.

During the fourth quarter of FY96, major software changes were made on the tester to enable life-cycle testing to continue on the ABSOLYTE II. In addition, a problem with the data transfer from the tester to the data base was encountered. Because of these issues, testing of this battery was temporarily suspended. However, life-cycle testing will continue in FY97.

Yuasa-Exide Dynacell DD Modules (Type DD-35-7)

In March 1995, Yuasa-Exide provided SNL with 10 Dynacell DD modules (Type DD-35-7). Seven of these modules were forwarded to PG&E for testing at their new Battery Test Lab, while the remaining three modules were retained by SNL for evaluation. The modules kept by SNL were configured into a series string. Each module consists of four VRLA cells, except for the third module of the string. This module has only three cells because one cell was removed due to a low open-circuit voltage of 0.5 V when received by SNL. Below are the developer's specifications and test limitations for this unit:

Physical Parameters

Weight: 767.34 kg/unit or 255.8 kg/module

Volume: 150 L/unit or 46 L/module

Dimensions: 42.9 cm (l) × 37.95 cm (d) × 92.33 cm (h)/unit or 13.03 cm (l) × 37.95 cm (d) × 92.33 cm (h)/module

A "module" is 4 interconnected cells.

A "unit" is 3 interconnected modules.

Unit Ratings

Nominal string voltage open circuit (OC): 23.3 V @ full SOC (11 cells)

Nominal individual cell voltage (OC): 2.12 V @ full SOC

Capacity: 110 Ah @ 8-hr rate to 10.25 V (1.75 vpc) cutoff (13.5 A for 8 hr)

Energy: 2.5 kWh @ 8-hr rate to 19.25 V (1.75 vpc) cutoff

Charge/Discharge Termination Conditions

Charge:

Maximum Charge Voltage: 26.4 V (2.4 vpc)

Maximum Charge Return: 150%

Maximum Temperature During Charge: 43°C (110°F)

Discharge:

Minimum Discharge Cutoff Voltage: 11.0 V (1.0 vpc)

Maximum Discharge Starting Temperature: 29°C (85°F)

Test Objectives

A test plan was developed by SNL, and the objectives of testing are as follows:

1. Confirm the electrical performance ratings.
2. Evaluate the battery's capability to meet requirements for renewable energy applications.
3. Determine the service life of the battery.

Testing of the battery started in July 1995. The first cycle performed on the battery was a C/8 (13.5-A) discharge followed by an equalizing charge. The charge current started at 44 A and was allowed to taper until the voltage reached 25.85 V or 37 hr had passed. During the next 18 cycles (Cycles 2 through 19), the battery performed C/8 discharges to 19.25 V. For these cycles, the battery was charged at a constant current of 30 A to 25.3 V or an 8% overcharge, whichever came first. For the next 20 cycles (Cycles 20 through 39), the battery was discharged at different rates including C/3 (36.2 A), C/12 (9.3 A), and C/8. A Peukert plot, based on the results of these cycles, is shown in Figure 4-6. The charge regime for these cycles was the same as that for Cycles 2 through 19. Capacity tests at a C/8 discharge rate were performed for Cycles 45 through 53; however, the charge regime was modified slightly. A two-step charge was started. The first charge (a standard "D" charge) (see Table 4-8) was at 44 A to 25.85 V or 5% overcharge followed by a 3-A charge to 26.95 V. Cycles

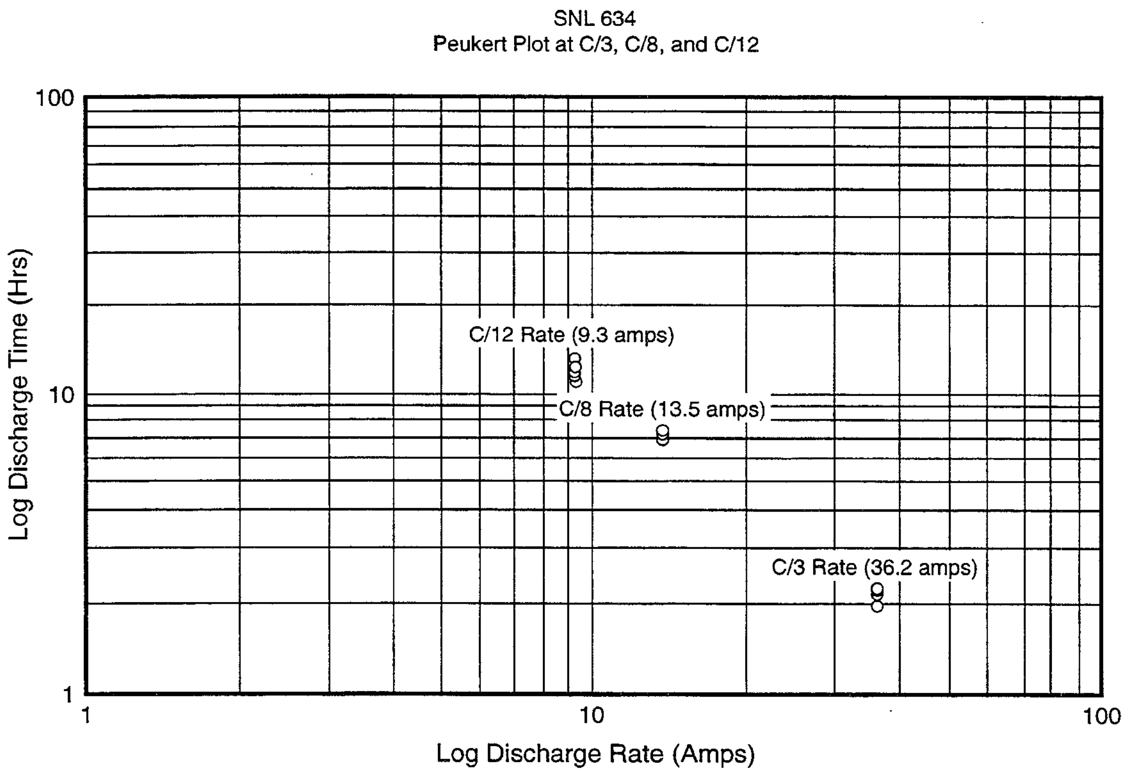


Figure 4-6. **Peukert Plot of Yuasa-Exide Dynacell Battery Constant-Current Discharges.**

54 through 62 were also discharged at a C/8 rate, but additional changes were made to the charge regime. A 5-min wait period was added between Charge 1 and Charge 2 (a standard "E" charge). This was done to ease the transition from 44 A to 3 A. Cycles 63 through 100 were also performed at the C/8 discharge rate, but the charge regime was again changed. For these cycles, the time duration of Charge 2 was increased to 8 hr to increase Ah and to stabilize the capacity. This cycle regime is identified as a standard "F" charge. Figure 4-7 is a plot of Ah removed and Ah returned during the 50 plus cycles performed in FY96. Once the final charging regime was selected, the testing results appeared to become more stable. Life-cycle testing will continue until the battery has lost 20% of its rated capacity.

Lead-Acid SLI Battery Testing

Community Power, a U.S. company, contacted SNL for testing assistance on batteries slated for use in PV systems in Indonesia. Although this battery is not particularly suited for PV applications, restrictive Indonesian import rules that prohibit the import of lead-acid batteries required that Community Power and their Indonesian customers use locally produced Pafecta Yuasa lead-acid SLI batteries, as there are no deep-cycling batteries manufactured in Indonesia.

The batteries (Table 4-9) arrived in September 1996, dry charged, which meant electrolyte that was prepared by SNL personnel in accordance with the manufacturer's specifications had to be added to the batteries.

After electrolyte was added, a two-step formation charge was performed (Table 4-10). Step 1 entailed a constant-current charge at the C/20 rate for 20-24 hr. Step 2 was performed using a constant-current charge at the C/6 rate for 5-6 hr. Following the formation charge, a capacity verification cycle was performed. Discharging was done at the C/5 rate and recharge also at the C/5 rate to 120% of discharge capacity.

The goals of this test are defined as follows:

1. Obtain a maximum number of daily PV battery cycles.

2. Establish a reliable battery low-voltage disconnect (LVD) level for the electronic PV system controller.

3. Assess battery performance in an application not normally suitable for lead-acid SLI batteries.

Table 4-8. Standard Charge Regimes

"A" Charge	"B" Charge	"C" Charge	"D" Charge	"E" Charge	"F" Charge
Charge at 30 A to a 8% over-charge or cutoff at 25.3 V	Charge at 30 A to an 8% over-charge or cutoff at 25.85 V	Charge at 44 A to a 5% over-charge or cutoff at 26.4 V	Charge at 44 A to a 5% over-charge or cutoff at 25.85 V	Charge at 44 A to a 5% over-charge or cutoff at 25.85 V	Charge at 44 A to a 5% over-charge or cutoff at 25.85 V
5-min rest	5-min rest	Charge for 2 hr at 2 A or cutoff at 26.95 V	Charge for 2 hr at 3 A or cutoff at 26.95 V	5-min rest	5-min rest
Wait until one or more thermo-couples show temperature below 29°C	Wait until one or more thermo-couples show temperature below 29°C	5-min rest	5-min rest	Charge for 2 hr at 3 A or cutoff at 26.95 V	Charge for 8 hr at 3 A or cutoff at 26.95 V
		Wait until one or more thermo-couples show temperature below 29°C	Wait until one or more thermo-couples show temperature below 29°C	5-min rest	5-min rest
				Wait until one or more thermo-couples show temperature below 29°C	Wait until one or more thermo-couples show temperature below 29°C

Note: All cycles start with a C/8 (13.5 A) discharge to 19.25 V followed by a 5-min rest.

4. Provide consultations on the operational set points and charging strategy for the proposed Alternative Power Technologies (APT) charge controller for the Community Power system.

PV cycling (Table 4-11) will consist of shallow discharging of the battery followed by a partial recharge, thus simulating a PV day. This process is repeated several times until the battery reaches the LVD, roughly equal to a 50% battery SOC. At this point the battery is then fully recharged to 120% of its discharged capacity and PV cycling is resumed. This process is repeated until the battery is unable to provide an adequate number of PV cycles.

VRLA Reliability Improvement Project

VRLA batteries have been commercially available for more than 10 yr and have been enthusiastically embraced by users of UPSs because of the anticipated reduction in maintenance costs and smaller footprint available with this technology. As field experience has accumulated, it is becoming more widely appreciated that VRLA batteries are more sensitive to their operating conditions than flooded lead-acid batteries. This is particularly true under conditions such as elevated temperatures or overcharging, which promote battery dryout in starved-electrolyte designs, thereby shortening battery life compared to what users are accustomed to in a float-type application. Much anecdotal evidence has circulated over the past few years concerning premature loss of capacity or thermal runaway incidents involving VRLA batteries. Although the majority of recent VRLA failures can be attributed to abusive environments or improper float-charging conditions, there is a lack of confidence among current users that all of the potential VRLA problems have been identified. All of this information has made potential utility battery customers more reluctant to adopt BES technology, particularly if VRLA designs are being proposed.

Because SNL believes that the VRLA battery technology does offer real advantages in utility and renew-

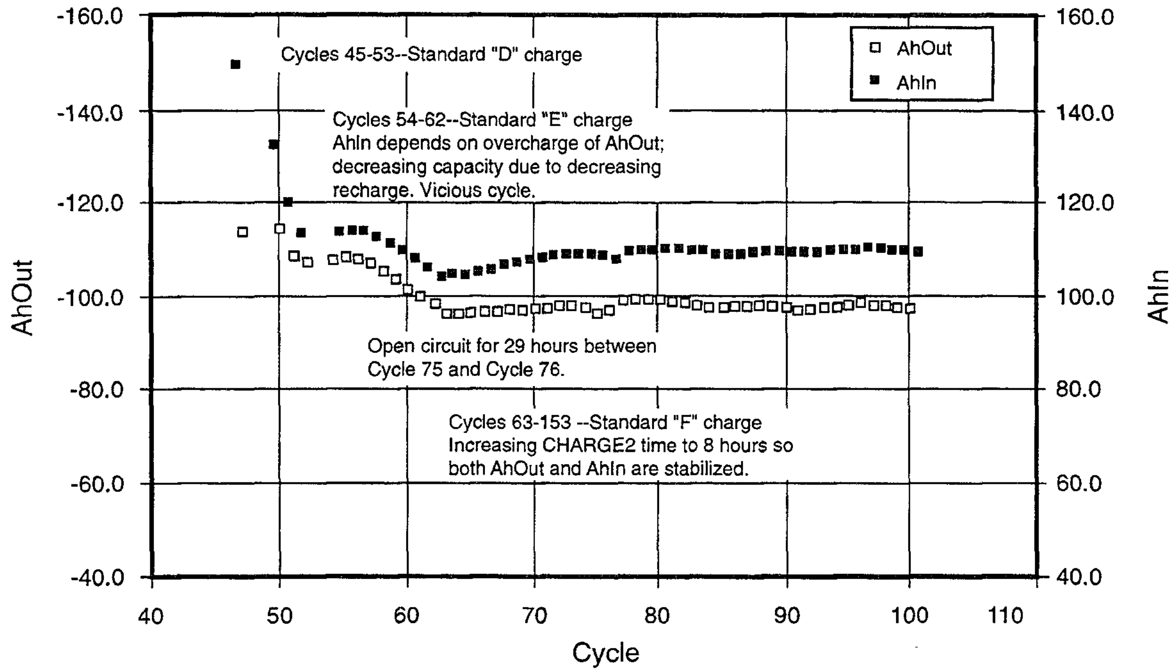


Figure 4-7. Life-Cycle Capacity Plot at C/8 Discharge Rate for Yuasa-Exide Dynacell Battery.

Table 4-9. Community Power Batteries Tested by SNL

Model Number	N-40	NS-70	N-100
Capacity, Ah*	40	65	100
Voltage	12	12	12

* At C/20 rate.

Table 4-10. Two-Step Formation Charge Amp-Hours

Model Number	N-40	NS-70	N-100
Amp-Hours of Charge	39.11	62.85	98.52

Table 4-11. PV Cycling Regime for Community Power Batteries

Model Number	Daily Load	Daily Recharge	Recharge after LVD
N-40	9.7 Ah @ 2.85 A	8.7 Ah @ 2.34 A	120% charge @ 2.34 A
NS-70	14.9 Ah @ 4.42A	13.4 Ah @ 3.55A	120% charge @ 3.55 A
N-100	19.6 Ah @ 5.54 A	17.6 Ah @ 4.73 A	120% charge @ 4.73 A

able energy applications, a VRLA reliability improvement project is being planned. The primary objective of this project is to determine whether VRLA designs are capable of a reasonable cycle and calendar life under typical utility battery operating conditions and use modes. The sensitivity of VRLA designs to their environment and charging conditions could also be investigated in such a program through independent testing that would more thoroughly define the limits at which battery life is affected. If battery performance under expected utility operating conditions is not satisfactory, or if previously unrecognized failure modes are discovered, then design or material changes could be suggested to address those needs. SNL anticipates that heavy involvement and cost sharing by the VRLA battery manufacturing industry would be necessary for this project to succeed. During FY96, SNL presented these issues to many stakeholders, obtained feedback on industry concerns and interest in participating in such a project, and strove to determine how a group could be formed to validate the reliability of the core VRLA technology in utility applications.

Status

During the second quarter, personnel from SNL and Endicon visited Yuasa-Exide, Inc., to discuss recent developments in the ESS Program and to obtain the Yuasa-Exide perspective on the utility battery market. VRLA battery reliability perceptions and needs were also covered as part of this meeting. Several causes for VRLA failures were discussed, including dryout, plate growth, and improper charge control. Yuasa-Exide feels that a major disconnect still exists between customer expectations and actual battery life in many applications of VRLAs. It was suggested that it would be beneficial to establish a consistent set of requirements for equipment such as PCSs that must interface with the battery in utility or standby power systems. SNL may be able to help develop such a set of requirements. This issue is related to reliability because of the importance of charge control as a major factor that affects battery performance and life. Interest was also expressed in independent testing of Yuasa-Exide products that are intended for the utility battery market.

Further discussions were held on generating a proposal for collaboration on VRLA battery performance and reliability evaluations. Ways to structure a program that would encourage participation by a wide cross section of battery manufacturers need to be found. This will likely be difficult because of the potential sensitivity of some of the test data that could be generated. Informal contacts with other manufacturers indicate at least a general interest in pursuing discussions about what the reliability issues are. Yuasa-Exide has also continued to express interest in collaborating with SNL on testing of some of its specific sealed-battery products. This work could be done as a separate project or might possibly be incorporated as part of a larger reliability study. SNL has not responded to Yuasa-Exide at this point because the content of a more general reliability study that could be supported by a group of manufacturers has not been clearly established. A planning meeting among the interested participants will likely be necessary to reach a consensus on the goals and content of this more generic program. Teaming with other organizations that have existing programs in related areas, e.g., the Advanced Lead-Acid Battery Consortium (ALABC) program of the International Lead Zinc Research Organization, Inc. (ILZRO), is also being explored as a way to include a wider range of participants and leverage some of the costs.

Sodium/Sulfur Applied Research at SNL

SNL is concluding an effort to develop prototype thermal fuses for sodium/sulfur batteries. Thermal fusing addresses a concern that individual cell failures generating electrical shorts could lead to catastrophic failure of a battery. The objective of this task is to demonstrate the feasibility of a fuse concept for use in the sodium/sulfur battery technology. Cast metal fuses appear to be able to satisfy many of the requirements on an initial list obtained from Silent Power, Ltd. (SPL), a sodium/sulfur battery developer.

The only pure material with a melting temperature near the desired fusing point for a sodium/sulfur battery is zinc, with a melting point of 419.5°C. However, this is still below the 450°C fusing point that would be considered ideal. Zinc also has the disadvantage of oxidizing very rapidly, particularly at its fusing temperature. The oxide shell that forms on the surface of the molten zinc seems to hinder the fall of the drop off the electrical leads to the fuse, and the circuit often remains unbroken. Although it has been shown that the operation of the zinc fuse can be made more reliable by increasing the gap between the electrical leads, some effort was expended to identify alternative fuse materials with both higher melting points and less tendency to oxidize.

Status

A series of high-temperature solder alloys was evaluated for use in the thermal fuse. Functional testing was completed on trial fuses cast from four different binary alloy compositions. Electrical continuity was measured while these samples were heated in air and also, in some cases, in an inert atmosphere where oxidation should not be a factor. An improved carbon mold has been used for casting trial fuses with different gap widths between the leads. This mold allows gaps of up to 20 mm to be created for evaluation of whether the various candidate fuse materials differ in their ability to drop cleanly from the leads during a fusing test. Prior to casting the trial fuses, the alloy formulations were characterized by differential scanning calorimetry. Their melting points were as expected, which indicates that the formulations were correct and that no impurities had been inadvertently introduced. Onset temperatures for the melting endotherms ranged from 427°C to 510°C, depending on the composition.

In an inert atmosphere of argon, most of the trial alloy fuses with a 5-mm gap between the leads did open (see Figure 4-8), although in a few cases this did not occur until well above the alloy melting point. The molten drop still tended to hang in place for the more viscous of these materials. In air, the test results were less promising at a 5-mm gap, with most samples failing to open. Figure 4-9 shows a typical set of results. These alloys appear to also be oxidizing to some extent, similar to the case with zinc. When the gap width was

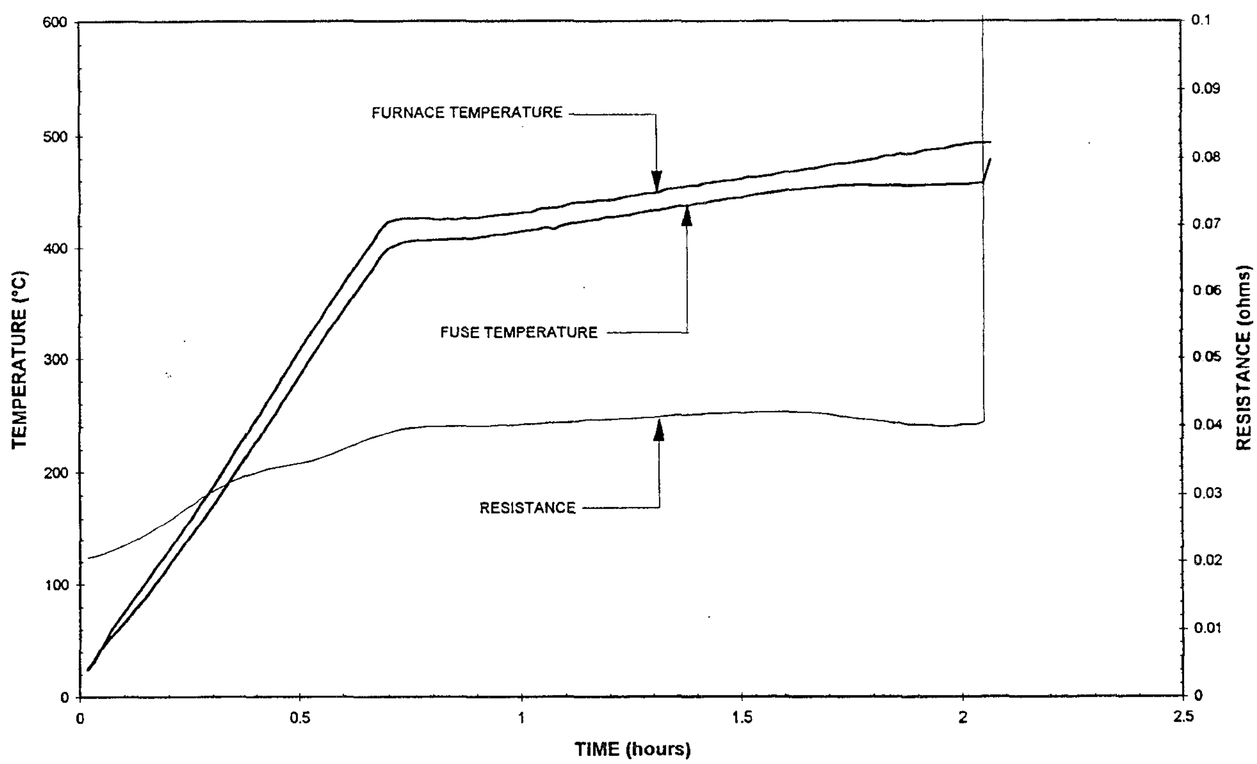


Figure 4-8. Fusing Test Results in Argon on an Alloy Fuse with a 5-mm Gap Between the Leads.

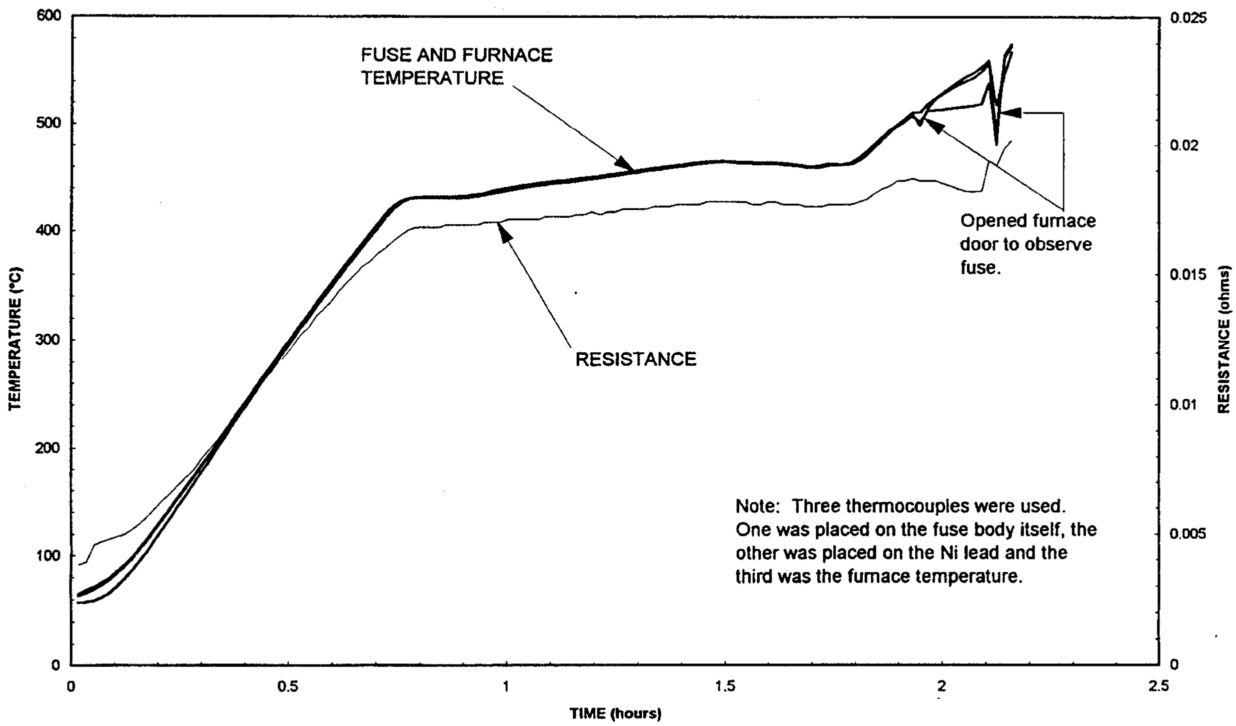


Figure 4-9. Fusing Test Results in Air on an Alloy Fuse with a 5-mm Gap Between the Leads.

increased to 10 mm, most of the alloy fuses did function successfully in air. Data from a successful fusing test are shown in Figure 4-10. Increasing the gap width is the simplest way to obtain a workable fuse design with the alloys. A 10-mm gap width would not increase the overall size of the fuse too much for it to fit into most sodium/sulfur battery modules.

The most promising candidate for the fuse material was an alloy that melts at about 460°C on the differential scanning calorimeter. Trial fuses made with this material opened in air at temperatures of 470°C or below when the gap width in the fuse was set at 10 mm. All of the experimental data from the fusing tests and other material characterization experiments have now been reduced. The collection of this information into a summary report is well under way and a draft will be circulated for review shortly.

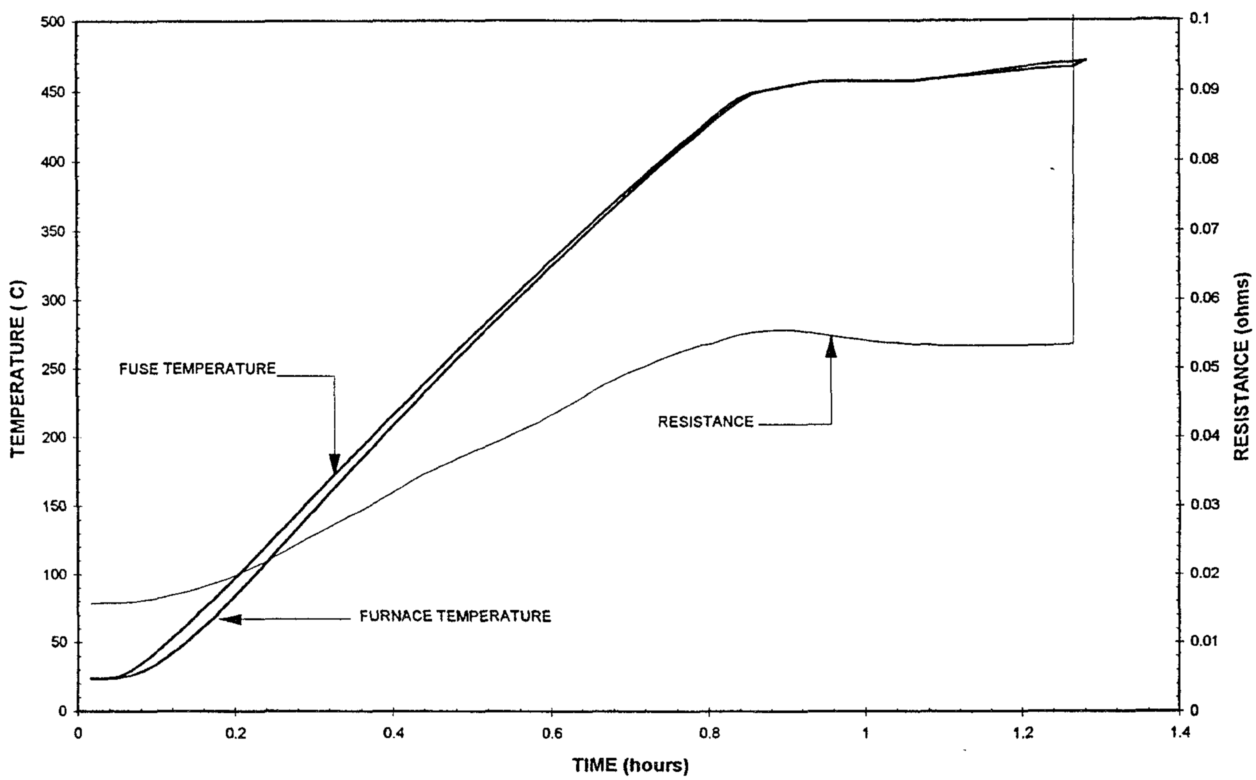


Figure 4-10. Fusing Test Results in Air on an Alloy Fuse with a 10-mm Gap Between the Leads.

5. Integration and Implementation

Introduction

Activities in the Integration and Implementation element involve pursuing a strategy that will reduce the inefficient, one-of-a-kind system engineering historically required when an energy storage system is designed and built. A "modular battery" system approach has been adopted as the preferred method to achieve system flexibility and the lowest possible cost. Under this approach, the major subsystem components (battery and electrical) are designed as separate modules so that integration can occur either at the factory or the utility site. From a cost perspective, the modular approach permits more efficient engineering, design, and manufacturing processes. Performance and service-life qualification of hardware incorporating prototype designs will also be performed. This activity involves the detailed characterization of performance, maintenance requirements, and reliability (service life) of integrated systems at relevant utility sites. The qualification of hardware incorporating prototype designs and associated manufacturing methods represents the final step of engineering development.

Factory-Integrated Modular Storage (FIMS) Systems

One of the preferred system-integration strategies involves factory assembly and testing of modules that each contain a storage subsystem, PCS, and controller. The motivation for producing these "factory-integrated modular" (FIM) systems is to save the 30-to-50% cost burden typically associated with custom engineering designs, on-site installation labor, and startup times.

A number of FIM technology designs progressed under the ESS Program during FY96, several using the ACBC lead-acid-based battery and the zinc/bromine battery developed under the ZBB contract. The development associated with the near-term ACBC technology is at the production-engineering phase (precommercialization). The ACBC tasks will be completed with FY96 funding. This situation contrasts with the preliminary battery development that is being completed this year for the two advanced batteries (sodium/sulfur and zinc/bromine). During FY96, work on the zinc/bromine battery system will involve prototype engineering and subsequent field demonstration.

AC Battery Development Contract Wrap-Up

Several important tasks were not completed following delivery of the AC Battery PM250 prototype because of funding limitations in the original contract. Several contracts were placed with Omnion Power Engineering to complete these tasks. One contract was placed to support maintenance requirements of the PM250 during field testing. The purpose of this contract is to provide field engineering support and repair materials for hardware failures and maintenance during the characterization and life testing of the PM250 prototype. A second contract was placed to complete the final report and cost projections for the AC Battery prototype development program. The purpose of this second contract is to complete the documentation for the AC Battery project.

Status

A draft final report on the PM250, *Final Report on the Development of a 250-kW Modular, Factory-Assembled Battery Energy Storage System*, was received for review in early June. Following review and markup, the PM250 final report will be published as a SAND report for distribution early in FY97. The *PM250 Prototype Production Cost Estimate Report* is also expected to be completed and published in early FY97.

Transportable Battery Energy Storage System (TBESS)

The goal of this project is to further the deployment and evaluation of prototype battery systems built with commercially available and advanced components in typical utility operating environments. The project covers the design, fabrication, siting, installation, testing, and reporting on the system. The system will be designed such that it can be moved to a new location (on the same or on a different utility grid), installed, and tested. During these projects, the systems that are developed will be used by one or more utilities over a multi-year period to obtain field data at more than one site to prove the reliability, functionality, and cost-effectiveness of the system and to determine the benefits of BES in electric utility systems. Current plans are for the entire project to span a five-year period. A significant cost-share (about 50%) is required for this project.

TBESS Development

This project is part of a collaborative activity known as the Transportable Battery System (TBS) Program, which is an initiative of DOE and EPRI. A contract was to be placed for the design, fabrication, and testing of a utility-scale transportable battery system to be evaluated at multiple sites in partnership with a selected utility. SNL collaborated with EPRI on the development of the SOW for this project, and a similar project was initiated by EPRI. An RFP was issued by SNL in late FY95. The goal of the project was to further the deployment and evaluation of prototype battery systems built with commercially available and advanced components in typical utility operating environments.

Status

On August 5, 1996, negotiations were completed and the ESS TBESS contract was awarded to AC Battery Corporation, a subsidiary of GM based in East Troy, Wisconsin. Under the terms of the contract, ACBC will design, integrate, and test an AC Battery PQ2000 on a fully mobile low-boy trailer. During the first quarter of FY96, early in the request for quotation (RFQ) phase of the TBESS project, the DOE Program Manager suggested that the project focus on solving high-visibility power-quality problems. Consequently, modifications to the final RFQ required that the TBESS be operated in a power-quality mode at a power level of 2 MW for 15 sec. Terms of the contract also required substantial cost sharing in which SNL/DOE would pay for the design and development phases of the activity and the successful bidder and utility partner would cover all costs for system hardware and field testing.

The first deliverable on the contract, received on August 28, 1996, consisted of a conceptual design drawing, a detailed project schedule, and a detailed system site plan. The initial schedule indicated that the TBESS would be delivered to the first test site and remain there for a period of 6 mo. Terms of the contract require that the TBESS be moved to a second site, set up, and operated for a period of 6 mo. The final report for the project is due April 30, 1999.

Figure 5-1 shows the initial conceptual design for mounting a PQ2000 system, consisting of the PQ2000 battery container, the electronic selector switch, and the system output transformer on a standard-length low-boy trailer. The only interconnection required at the host site will be to the 480-VAC service entrance at the utility test site, which will minimize setup time at the customer's facility.

Because of internal conflicts within the original utility partner's business sector, the utility partner withdrew from participation on the TBESS contract in late September, causing major concern among the project participants. ACBC immediately began negotiations with other utilities who had expressed early interest in

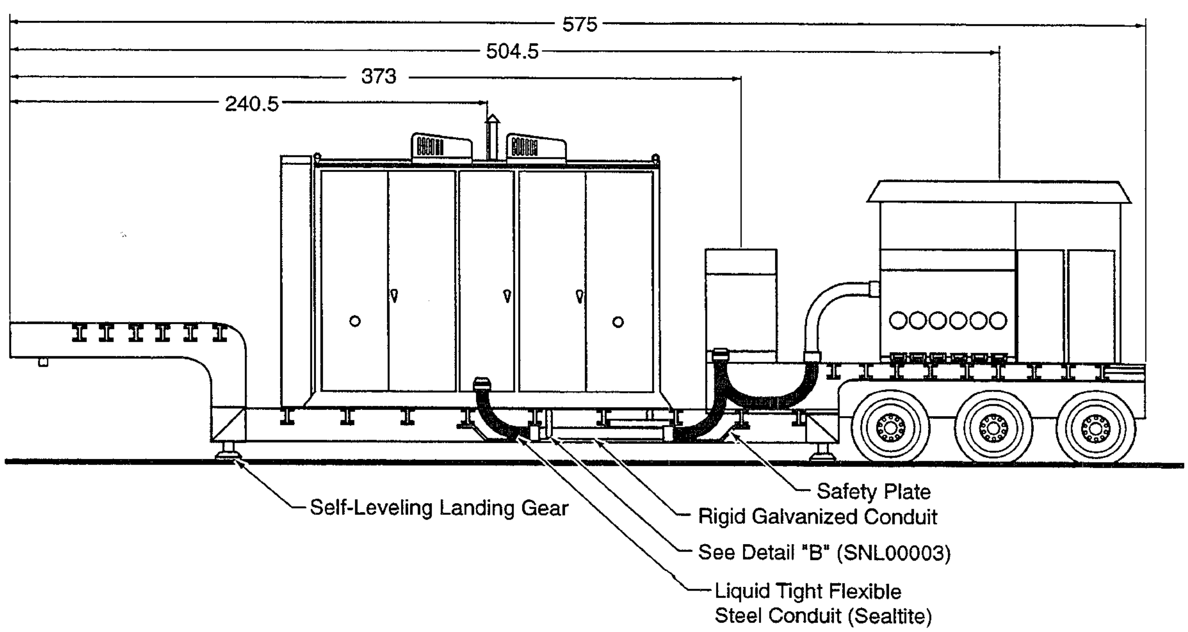


Figure 5-1. Initial Conceptual Design for the TBESS.

the TBESS project. It is anticipated that ACBC will identify a new utility partner early in FY97.

Advanced Battery Energy Storage System (ABESS)

ABESS Development

The Preliminary Opportunities Analysis performed during FY94 showed that advanced batteries have a clear and important role in BES. The VRLA technology has the potential to satisfy most UES applications. However, its primary deficiency is with those applications that place importance on footprint and portability and where higher energy capacity is required (duration of more than 1 hr). Relevant large-volume applications include T&D facility deferral, renewables, and customer/transit system peak reduction. Advanced batteries (e.g., sodium/sulfur and zinc/bromine) may fill this void.

During the 1980s, the DOE-sponsored development of the UES sodium/sulfur and zinc/bromine technologies permitted their conceptual feasibility to be validated and set the stage for focused subsystem development. In the recently completed contracts with Silent Power, Inc. (SPI) and ZBB, an iteration of component engineering has been performed to resolve specific utility-battery feasibility issues. Also, preliminary battery engineering is now being completed that will identify any remaining long-term development requirements and, importantly, provide the basis for entering the relatively expensive battery-level engineering development and demonstration phase. Concurrently, development of other candidate advanced batteries with the desirable characteristics of higher energy/power ratio and relatively low footprint has also been proceeding with both private and public funding. The focus of these latter efforts is typically on portable consumer or electric vehicle applications. Nevertheless, some compatibility between the capabilities of these batteries and UES requirements may exist.

The establishment of a meaningful role for advanced batteries in UES applications combined with their progressing development status warrants a new and dedicated effort to ensure that viable advanced battery systems will be available by the turn of the century.

This task will address the need described above, and a contract will be initiated during FY96. Because the identification of customers for this technology is the critical element to the final, production-engineering phase of development, the focus or end product of this task is to be a field demonstration at a utility or customer site. This prototype integrated system (battery, PCS, controls) is to perform one or several UES applications. As such, the active participation of an advanced battery developer, a utility customer, and a PCS manufacturer will be required. In addition, targeted applications must be selected that are consistent with the needs identified in the Opportunities Analysis and that cannot optimally be satisfied with lead-acid technology. Lead-acid battery technologies are precluded from consideration. Finally, a significant factor in the contractor selection process is that a high probability for project success must be demonstrated. If funding is available, more than one award may be made.

The SOW will, in general, cover the following tasks:

- ABESS specifications and field-test plan
- Engineering design
- ABESS fabrication
- Acceptance testing
- Documentation and training for field testing
- Preparation for testing
- Field testing
- Decommissioning

The principal activities to be performed during FY96 will involve the initiation of a contract. This will include (1) formulation of an SOW and evaluation criteria, (2) release of an RFQ to all qualified domestic suppliers, (3) evaluation of the proposals and contractor selection, (4) contract placement, and (5) initiation of the SOW.

Status

The RFQ for this project was released by SNL in mid-January 1996. The deadline for quotes was March 1996. Several proposals were received; however, additional information was needed in order to adequately evaluate the proposals. A letter requesting additional, specific information from the proposers was sent out and the deadline for submission extended to July 1996.

System Field Evaluation

Qualification of hardware that incorporates prototype designs will also be performed in this element of the program. This activity involves the detailed characterization of the performance, maintenance requirements, and reliability (service life) of an integrated system at relevant utility sites. Once the usefulness of these designs is proven (qualified), private industry will take responsibility for completing the final "commercial product" phase of engineering development.

AC Battery PM250 Prototype Renovation Project with AC Battery Corporation

After completion of the AC Battery PM250 fabrication and testing effort conducted by Omnion Power Engineering Corporation, a contract was placed with AC Battery Corporation (ACBC) for the maintenance and upkeep of the AC Battery PM250 prototype while it was being prepared for resumption of testing following the retrofit of the system battery complement. The ACBC prototype container had to be renovated before testing of the system could resume because the container had sat idle for over a year while the modules were being retrofitted at Delphi Energy Systems. Also requiring attention were deficiencies in the module's PCS printed circuit boards that resulted from field engineering modifications made while the initial test program was under way and errors in the system software that were discovered during initial field testing.

Status

Final testing and qualification of the AC Delco AES 2010 battery was completed by the Delphi Energy team early in the first quarter of FY96. Preliminary results of the tests on the first preproduction batch of batteries indicated that a revised design had substantially enhanced battery cycle life. A full production run for the complete battery set was completed in early December 1995. SNL requires that a random sample of six batteries be selected and shipped to SNL for the purpose of cycle testing the batteries at the SNL battery laboratory. Delphi shipped six batteries to SNL in mid-January 1996.

After removal of the PM250 container from the PG&E MGTF test pad during the second quarter of FY96, the PM250 container underwent complete refurbishment and checkout at the AC Battery facilities in East Troy, Wisconsin. Initial evaluation of the container at AC Battery indicated that multiple problems had occurred during the long period that the container sat idle on the MGTF test pad while the modules were being retrofitted with new batteries at Delphi Energy Systems. During the third quarter of FY96, the eight PM250 modules, complete with new AES 2010 batteries, were thoroughly checked out in the Delphi Energy Systems container in Indianapolis, Indiana. The modules were shipped to AC Battery during the fourth quarter of FY96. The systematic checkout of the container electronics and module PCSs performed by the AC Battery engineers and technicians resulted in the elimination of most problems, and startup is expected in early November 1996, when all of the modules are scheduled to be mated with the container for full-power testing. Cosmetic cleanup of the container shell resulted in a like-new appearance for the PM250 container, all evidence of weather and shipping wear and tear having been eliminated.

AC Battery PM250 Field Evaluation at PG&E

The AC Battery PM250 prototype testing program was idle throughout FY95 while new batteries were being evaluated for the retrofit of the entire battery complement. Information obtained from the initial field testing program at PG&E indicated that the batteries selected for the prototype were inadequate to support the AC Battery operational requirements. To acquire a volume production battery with the capabilities to support all AC Battery applications, a comprehensive evaluation program was undertaken by Delphi Energy Systems of Indianapolis, Indiana, a division of General Motors. Delphi Energy Systems is funding the battery selection and replacement activity. Testing of the new batteries in the renovated AC Battery prototype is scheduled to resume at PG&E in FY96 following the completion of the PG&E testing program for the PQ2000.

Status

Testing of the AC Battery PM250 prototype at the PG&E MGTF remained on hold throughout FY96 as the PM250 modules underwent retrofitting with new Delco AES 2010 batteries at Delphi Energy Systems in Indianapolis, Indiana. During the retrofit period, the empty PM250 container rested on the test pad at the MGTF.

To make room for PQ2000 test activities at the MGTF, the empty PM250 container and utility isolation transformer were removed from the MGTF test site and shipped to AC Battery early in the second quarter of FY96. While at AC Battery, the PM250 container is scheduled to undergo a complete checkout and refurbishment in preparation for its return to field life-cycle testing. The modules were scheduled to be installed during the first quarter of FY97, after which complete system testing will be conducted. The factory acceptance test of the PM250 is scheduled for the first quarter of FY97.

Field Test of PQ2000

Following the completion of the DOE Cooperative Agreement for the PQ2000 design, fabrication, and factory testing activity, the PQ2000 will be transported to the PG&E MGTF for field acceptance testing. SNL has responsibility for providing technical consulting services to the DOE Albuquerque Operations Office (ALO) Cooperative Agreement manager.

Status

The first PQ2000, which was designed and fabricated under a program jointly sponsored by PG&E, AC Battery, Omnion Power Engineering Corporation, and the U.S. DOE, was shipped from ACBC to the PG&E MGTF in mid-April. Following a successful shakedown test, the PQ2000 entered a comprehensive field test program. During the quarter, control strategies were evaluated to determine an optimum "sense and switch" algorithm that would minimize the number of battery use events triggered by small voltage excursions above minimum power quality specifications. The original switch strategy was based on a feeder switching concept that did not take into account the number of times a switching event took place as it determined which feeder was providing power of the best relative quality. In a battery source system, it is essential that a battery-supported event be initiated only when the primary feeder falls below minimum quality specifications. The implementation of the new algorithm resulted in a significant drop in switching events while allowing the PQ2000 to meet all minimum power quality specifications at the load.

During the test program, several iterations of the "reconnect strategy" were evaluated to establish appropriate criteria to meet when reconnecting the utility to the customer load at the end of a maximum battery discharge period, typically 10 sec. The original specification required that the PQ2000 restore connection of the customer load to the utility at the end of the maximum 10-sec discharge period irrespective of the condition of the utility. Based on experience gathered during field testing, it was determined that the utility would not be reconnected unless it met minimum quality standards. This condition was implemented when it was discovered that single phasing of three-phase motors resulted in their destruction when the utility was restored with one or two phases present. Implementation of this field engineering modification resulted in several months' delay in the testing program.

Preliminary test results demonstrate that the PQ2000 has the ability to effectively detect and eliminate voltage sags, voltage swells, and momentary outages. As utility service voltage exceeds a deviation threshold limit, the system's electronic selector device (ESD) executes the transfer to battery power. As Figure 5-2 illustrates, the PQ2000 is capable of switching to stored battery energy in approximately 1/4 of a cycle. The top waveform displays the recorded voltage and momentary outage that occurred on the utility supply line. The time required to get the output load voltage up to the expected utility supply voltage was measured at 1.6 ms, which makes the total event 5.4 ms in duration or 1/240th of a second.

Figure 5-3 illustrates the transfer back to utility power after the disturbance has cleared and the system has synchronized phase with the utility. A 2-sec delay before switching back to the utility service has been incorporated into the system's control program to prevent excessive transfer oscillation between utility and battery power. If the disturbance has not cleared after 10 sec, the system will shut down or execute a transfer of the critical load to a standby engine generator, if that option has been specified.

The current system has been validated for 10 sec of continuous or cumulative cycle runtime without a complementary recharge. Calculations and testing show that a 10-second discharge of the battery at the full rated output of the PQ2000 consumes less than 4% of its charge. The high-power, short-duration discharge capability of the Delco 1150 battery makes it highly suitable for the PQ2000 application.

Figure 5-4 shows estimated battery cycle life as a function of DOD. The Delco 1150 is expected to provide in excess of 3000 cycles over an expected life of more than 5 yr, given the application, duration, and frequency of voltage sags and momentary outages. Limiting discharge times to 10 sec balances DOD with cycle life expectations and thermal load limits of the system. The 10-sec limit more than matches the application requirements while substantially improving the battery cycle life and discharge performance.

A battery recharge cycle is initiated immediately after a discharge event. Battery modules are simultaneously but independently recharged using the proprietary algorithm designed specifically to maximize charge cycle efficiency of the Delco 1150. Laboratory tests conducted on individual batteries have shown that battery cycle life nearly doubled as a result of using the algorithm and contributed substantially to eliminating electrolyte stratification.

A major factor governing battery recharge time is DOD. Each second of discharge at 720 A requires 2-1/4 minutes of recharge to restore the battery to 90% of its

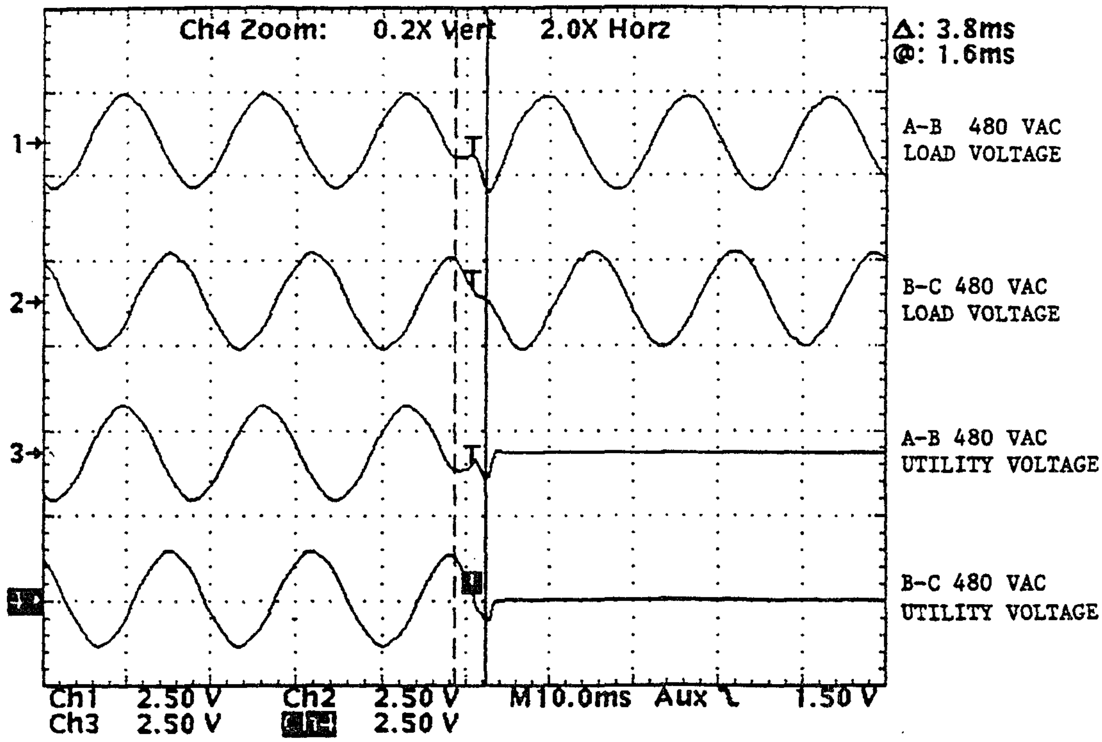


Figure 5-2. Voltage Interruption on One Phase of the Utility and Load Pickup by the PQ2000.

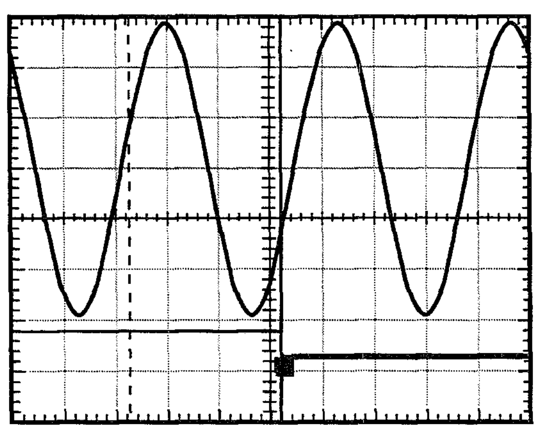


Figure 5-3. Synchronous Transfer Back to the Utility.

predischarge potential. Up to one additional hour is needed to restore the remaining 10% of the battery's potential for a continuous, full-10-sec discharge. Recharging may, however, be interrupted to service another disturbance.

Overall, the PG&E test program for the first PQ2000 yielded new and unanticipated information on the functional and operational requirements of a utility-scale power quality system. As a result, many field engineering modifications were made to the control strategies to meet PG&E engineering change requests; these modifications were based on practical operational requirements discovered during field testing activities. Testing continued throughout the year with sporadic interruptions while engineering fixes were implemented. The completion of the testing of the first PQ2000 is scheduled for late in the first quarter of FY97.

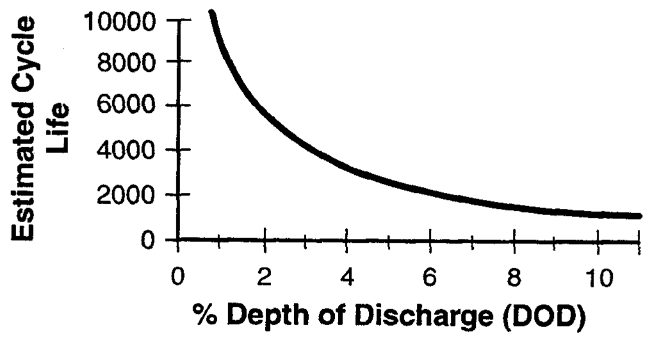


Figure 5-4. Battery Cycle Life Plotted as a Function of DOD.

Field Test of Final VRLA Battery Deliverable

As the final deliverable from the VRLA battery development contract, GNB furnished a 250-kW, 500-kWh battery for a field test. The site selected for this test was the GNB lead recycling center in Vernon, California, and a new contract was placed with GNB at the beginning of FY96 to carry out the field testing. GNB has installed a battery system at the recycling center to support critical plant loads during utility power outages so that no violations of air emission standards can occur. This system is capable of providing 3.5 MW of power to the plant for 1 hr and a peak power of 5 MW for 10 sec. The battery consists of two parallel strings of GNB 100A99 ABSOLYTE IIP VRLA cells. Each string contains 378 cells operating at a nominal 756 V. Battery energy is converted to plant AC voltage by three General Electric (GE) power conversion units, each rated at 1.25 MW.

The battery is also available for periodic block loading to reduce plant peak loads and demand charges. Operation of this system provides an opportunity to evaluate the performance of a large VRLA battery while it is used in an actual field application. Approximately 10% of the battery cells at Vernon were supplied by the ESS Program.

A remote communications link has been established between the Vernon site and GNB's engineering laboratories in Lombard, Illinois, which makes it possible to monitor all status screens of the control system, including those for battery status, plant power requirements, status of the power conditioning equipment, and alarm conditions from the remote terminal. The data presented by the battery monitor screens include battery voltage, battery current, battery temperature, and ambient temperature. Through a password-protected screen, it is also possible to operate the BESS from this remote terminal, either turning on the battery at specific power levels for plant support or carrying out battery testing.

Status

During the first quarter, trials were carried out to demonstrate the capability of the BESS to take over from the utility grid and provide power to support the operation of the recycling plant. In November, the following procedures were successfully completed as part of these trials:

- The plant was taken over three times from the utility at an "ON BESS" loading of 2377 kW.
- The battery system carried the "ON BESS" load for a cumulative period of 30 min (for three consecutive tests).
- The BESS was successfully synchronized with the utility feeder to return the plant load to the utility.
- The plant load shed algorithm that is used to shut down noncritical loads during "ON BESS" operation was verified.
- A 100-HP motor was successfully started while the plant was "ON BESS."
- Data were collected during these trials on plant harmonics and the response time of the battery and power conditioning equipment using a high-speed strip chart recorder.
- The operation of the BESS operator and display panels was verified, the battery SOC and discharge time remaining algorithms were tested, and the operation of data screens during charge and discharge was demonstrated.

- Volt-amp reactive (VAR) compensation during recharge of the battery was added, and ground fault alarms during battery recharge were tested.

Two training sessions for Vernon plant personnel responsible for operation and maintenance of the BESS facility were also held. At the completion of system testing, the battery will be turned over to the plant and will be operated like any other piece of plant equipment. GNB will retain an engineering role and will monitor the battery for proper operation to ensure optimized battery life. GNB will also verify life projections by testing and examining the battery.

Following the system trials in November, a list of action items was developed for correcting minor issues relating to the inverters, battery, and remote data acquisition. Most of these were directed at GE, which has primary responsibility for the power conversion equipment and the system electronics. All these action items were resolved by early in the second quarter. One of these issues was related to erroneous converter alarms during the system trials. The source of these alarms was traced by GE to a specific control board, which was replaced after a redesign of the circuitry. Discussions were also held between GE and GNB regarding limitations that have been identified in retrieving data from the BESS. These limitations prevent direct importing of data to a remote spreadsheet program. Specific data fields that GNB would be interested in retrieving for analysis were identified, and GE will provide a translator program that will allow this to be done. This will also allow absolute parameter values to be displayed, which is preferred over the percentage (0-100%) of a range that was initially displayed by the system.

During December 1995, the battery was tested and inspected. The battery delivered 98% of its rated capacity when discharged. Following this discharge, the battery was recharged and then given an equalization charge to force cells to vent. After the equalization charge, all ground faults resulting from the cells venting were located and neutralized. The battery was considered ready for normal system operation with the completion of these conditioning steps and was placed on open circuit awaiting completion of the electronics modifications.

GE continued to modify the system control software during the second quarter to eliminate certain control issues that were uncovered during the initial system trials conducted in the first quarter of FY96. This software modification work was carried out at the GE facilities in Schenectady, New York. The battery was also checked early in the second quarter to remove a few remaining ground faults that were discovered following the equalization recharge. GNB's field service technicians removed cells showing a ground fault condition, cleaned and neutralized the battery racks and cells with ammonia solution, and replaced the cleaned cells in their original positions. The battery was then returned to float charge so that it would be available to provide uninterrupted power to the Vernon facility in the event of a local power failure.

GNB also completed the collection of the baseline characteristics and performance capabilities of the battery installed at the Vernon BES facility. The following were among the data collected:

1. Impedance values of 156 sample cells were measured using the Elcor Model IMI801 impedance measurement meter. Average internal resistance of these cells was 0.22 mohm; the 3-sigma value was 0.05 mohm.

2. The float-charge voltage was measured for 312 battery cells. Average float-charge voltage was 2.250 V; the 3-sigma value was 0.023 V.

3. The discharge voltage and current for both battery strings was measured at 3-min intervals during a nominal 1500-kW discharge. A plot showing these data is provided in Figure 5-5. Additional data from this baseline discharge were transferred to an Excel spreadsheet file so they could be summarized in a statistical format.

While the BES system was in the standby mode, occasional instances were noted where the power control pair (PCP) inverters faulted. These faults were characterized by a sudden dip in battery string voltage for no apparent reason. This information, along with the PCP alarm/fault codes triggered during these periods, was forwarded to GE for analysis and corrective action, if required. There was no indication that the battery was discharged during these periods. It was also observed during battery baseline tests that estimated battery SOC deviated significantly from actual battery SOC during the early portion of a discharge. GE felt that changes to the algorithm that corrects for discharge rate and battery temperature would improve accuracy, and GNB requested a cost estimate to do this.

During the early morning hours of February 20, 1996, the plant did experience a utility outage, and the BES system did take over the full load of the plant. Although the utility power outage only lasted a few minutes, the battery system was configured for a "manual" reconnect to the utility, which never occurred. As a

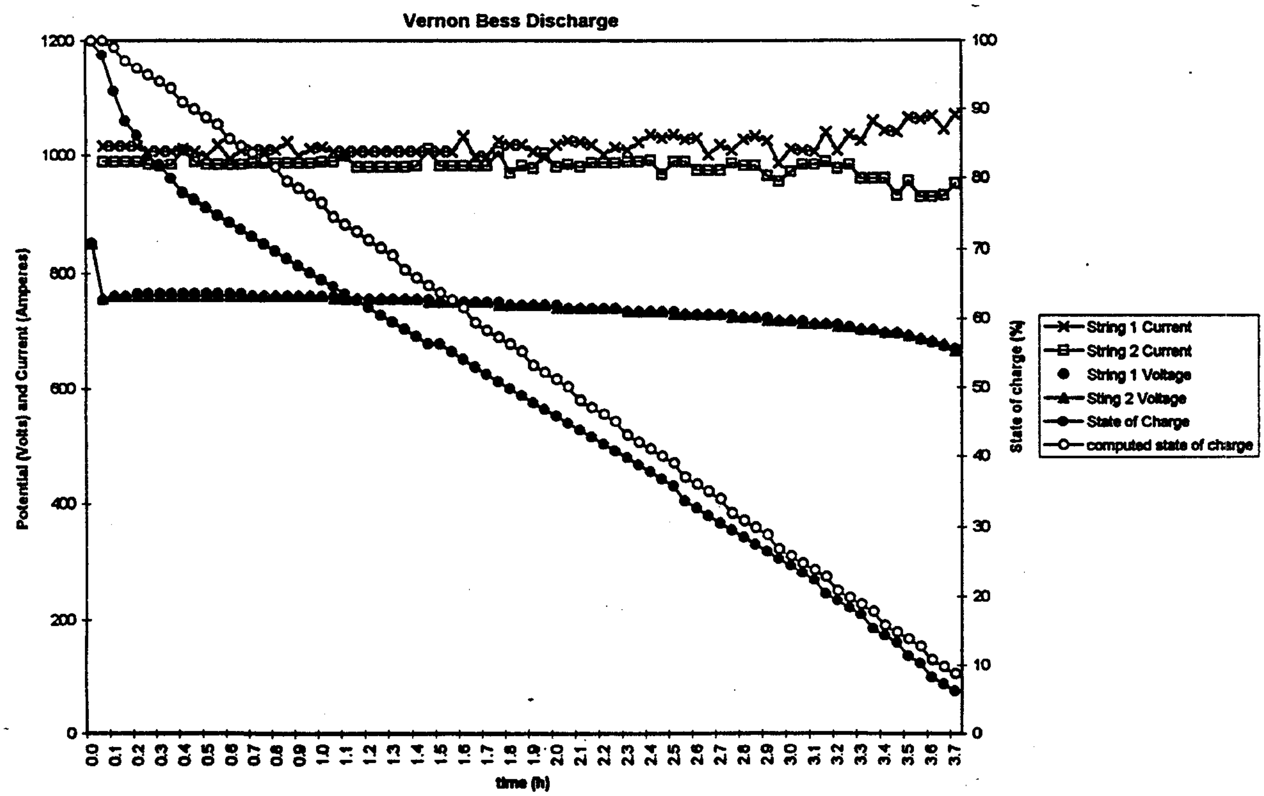


Figure 5-5. Discharge Voltage and Current for Battery Strings Measured at 3-min Intervals during a Nominal 1500-kW Discharge.

result, the battery was allowed to support the entire plant for over 2 hr, which completely discharged the battery. When the battery gave a low voltage alarm, the plant was finally manually transferred to the utility. The system has since been reconfigured for "automatic" restoration and reconnection to the utility once the utility's power feed has been restored. During the remainder of the second quarter, no further utility failures occurred and the battery essentially remained in a float-charge mode for the entire period, except for demonstrations during facility visits.

A test plan for the Vernon BES system was developed in accordance with the SOW requirements of the SNL contract. The plan covers the balance of the first year of this contract, through approximately October 1996. After establishing baseline characteristics for selected sample cells from the battery, three block-loading operational scenarios will be developed to collect battery trending and efficiency information. The plan is to operate the battery for a minimum of 1 mo at each of the operational scenarios. Information on the Vernon smelter's operating loads was collected daily to provide a basis for selecting the three block-loading scenarios.

GNB hosted visits to the BES facility by representatives of Metlakatla Power and Light and SNL in February 1996. During each visit, it was demonstrated how the BESS could take over part of the plant's load from the utility by increasing the BES contribution to the plant in steps from 0.5 MW up to 1.5 MW. Both local and remote control, as well as return of the plant to the utility and battery recharge, were also demonstrated. The facility tour included the battery, converters, switchyard, and control computer. A project review meeting was also held with SNL to discuss the test plan and schedule for all activities planned for the first year of the field demonstration.

It was proposed by GNB that organized visits to the Vernon facility be conducted in conjunction with the ESA meeting in May and the Institute of Electrical and Electronics Engineers (IEEE) T&D Show in the fall of 1996, since both will be in the Los Angeles area. The first of the seminars/workshops required by the contract might also be held to coincide with the IEEE T&D Show in order to take advantage of the good audience the show will attract, as long as no logistics problems are identified.

The battery was operated only in a "float" charge mode during the first part of the third quarter and was available for any power outage that might occur at the facility. While it was operating in this mode, further information and operational usage patterns regarding the plant's electrical load were collected. This information was needed to define three specific "block-loading" scenarios to exercise the battery and to reduce peak demand charges for the plant's electricity needs. During this time period, GE also made improvements to address discrepancies in the operation of the converters and electrical controls that were noted during the last test discharge of the battery.

Plant electricity usage was monitored for several weeks in April 1996, and the information obtained thereby was used to develop the first block-loading scenario under which some peak shaving using the BESS would be provided. Figure 5-6 shows a plot of the power consumption by the Vernon facility during an average April week. The City of Vernon Power & Light has expressed interest in these experiments and has asked to be included in the information loop that will survey and analyze the results. The city also volunteered a data logger to monitor the plant's power consumption. Although the GNB system already collected these data, the redundant system provided by the City of Vernon Power & Light was useful as a check on the accuracy of the GNB system.

The first of the three planned block-loading scenarios was implemented in May 1996 and was defined as follows: If between 1 p.m. and 7 p.m. the plant's electrical demand is greater than 3250 kW, the BESS will discharge the battery at up to 592 kW until the battery's calculated SOC falls to 50%. The typical week's electrical usage in April served as the basis for selecting this operational profile. It was expected that, on average, each weekday (Monday through Friday) the BESS would be discharged at about 100 kW during this period.

Figure 5-7 shows the battery load on May 29, 1996, while the BESS was operating under the planned block-loading scenario. Between 1 p.m. and 3 p.m., the battery accommodated a few low-power peaks; between 3 p.m. and 7 p.m., the battery was discharged at loads of up to 200 kW. Battery SOC was reduced to about 90% during this period.

The plant's electricity demand from the utility, shown in Figure 5-8, was steady at about 3250 kW during the period when the BESS was on line. These charts also show a peak in utility demand to about 4000 kW, when the BESS was taken off line and returned to charge. This utility demand was greater than was previously drawn by the plant and reflects the additional

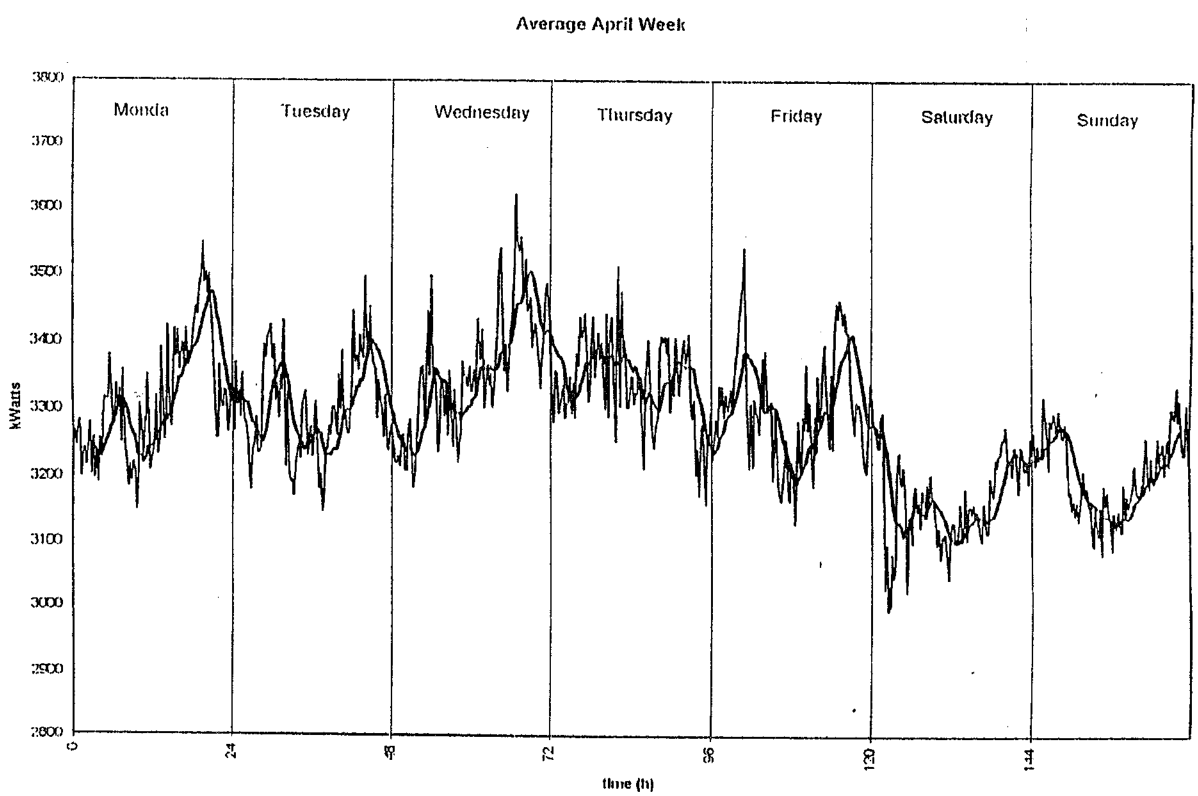


Figure 5-6. Power Consumption at GNB's Vernon Lead Recycling Center during an Average April Week.

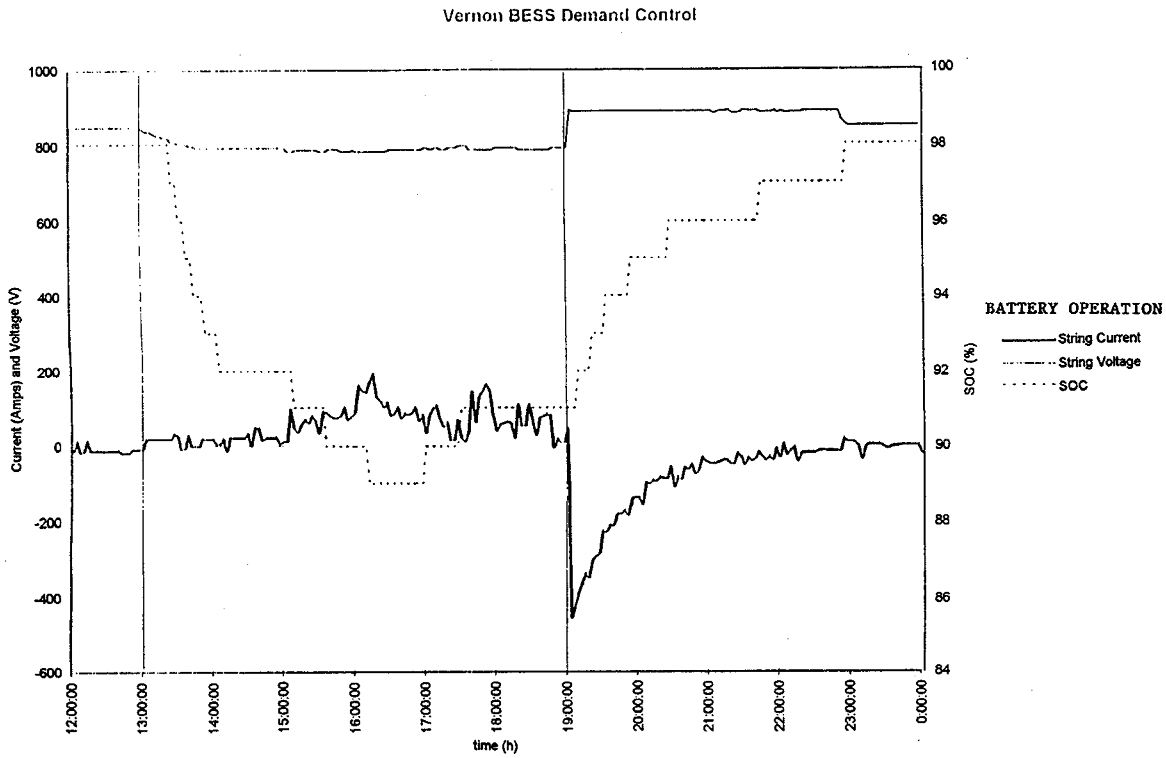


Figure 5-7. Battery Load on May 29, 1996, While Operating under the First Block-Loading Scenario.

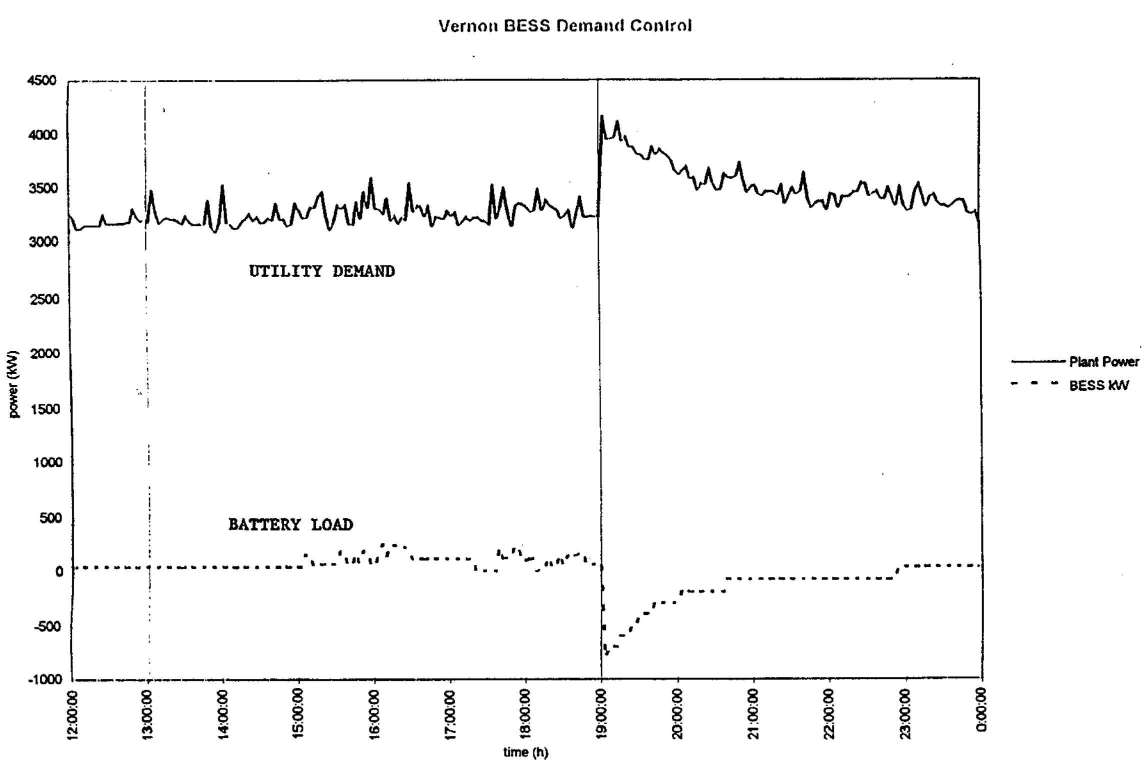


Figure 5-8. Vernon Lead Recycling Center Electricity Utility Demand While the BESS is On Line for Block Loading.

power required by the battery for recharge. GNB engineers attempted to reduce this peak by extending the window during which the battery was operational, thus pushing the recharge period for the battery out to a time when there was less base load demand by the plant (i.e., the early morning hours of each day). This was not an unexpected requirement for optimization of power consumption as part of the overall operation of the BESS.

Using an extended operational load profile (1 p.m. to midnight), the battery was operated for approximately 1 mo, functioning both during weekdays and over weekends. On a typical weekday, the battery output was on average approximately 100 kW; on weekends, the average BESS discharge was approximately 70 kW. Under this profile, the battery's DOD on weekdays was approximately 13%, whereas on the weekends the average DOD was only 9%. Charts of the plant utility draw and BESS output for a typical weekday and a typical weekend day are shown in Figure 5-9. Because of the relatively low DODs, a second operational scenario was planned that would allow the BESS to pick up loads above a 3000-kW plant demand. The goal was to exercise the battery more and achieve a greater reduction of the utility load during peak periods.

In May 1996, the Vernon BESS was the tour site for representatives from the ESA (formerly the Utility Battery Group (UBG)). Representatives from GNB and GE gave presentations to about 60 visitors at various locations in the Vernon BESS. Development of plans for the first of the project seminars required by the field testing contract was begun. Presentation topics that would be most beneficial to the audience attending such a seminar were discussed so that appropriate speakers could be suggested.

During June 1996, 2.5-MW discharges were conducted on each of the two parallel battery strings at Vernon. The purpose of these tests was to determine the heat generation at the individual cell terminal posts during this high-rate usage. Engineers monitored thermocouples that were placed at cell terminal posts, intercell connector bars, and interstack connector bars during the tests. All temperature values remained below the critical temperature criterion of 212°F. The greatest amount of heat was generated at the inter-stack connector.

In July, the Vernon BESS load peak-shaving profile was modified to increase the battery's DOD in this mode of operation. The new operating scenario had the following characteristics:

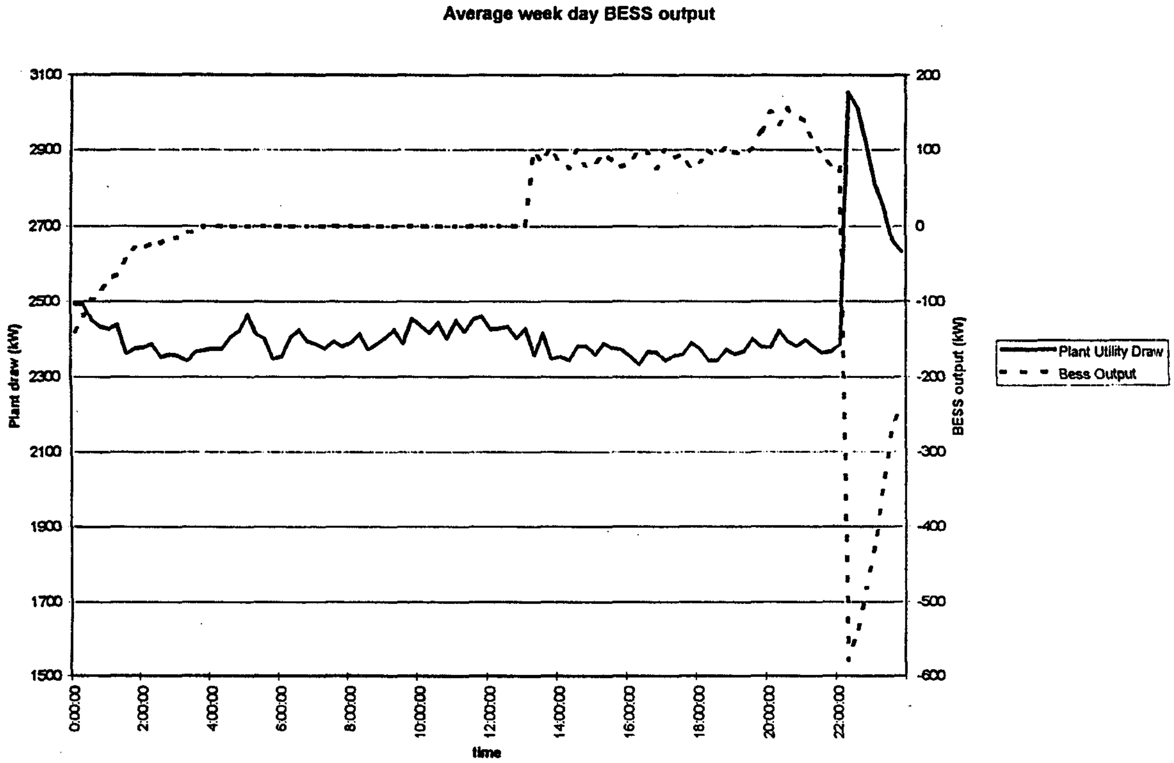
- The BESS is available for peak shaving between 1 p.m. and midnight.
- The BESS supplies plant demand greater than 2900 kW.
- Maximum discharge rate in a peak-shaving mode for the BESS is set at 592 kW.

Compared with the initial load peak-shaving scenario, which supplied plant demand greater than 3250 kW, this modified scenario discharged the battery to a greater depth with each daily cycle. Using the previous scenario, the nominal DOD was approximately 15%; the modified scenario discharged the battery to approximately a 50% DOD. A chart showing the battery SOC and the BESS output for a typical series of daily BESS cycles is provided in Figure 5-10.

GNB also learned during July 1996 from the City of Vernon (the electric utility provider) that certain timing constraints must be observed for the BESS operation to reduce GNB's electric bill. The monthly price of power at the Vernon facility is based on the highest peak reached between the hours of 1 p.m. and 7 p.m. from the first of each month onward. An appropriate time of day to operate the BESS had been selected, but the start of each operating scenario had to be timed so that it would be in effect on the first of the month for the impact on electricity cost to be determined. GNB planned to initiate an operational scenario sometime prior to the first of the month and then operate it through at least one week beyond the first of the next month to allow operation of the BESS to be fully reflected in the monthly utility bill.

The BESS system automatically alarmed due to detection of a ground fault during July 1996. Before the cell that exhibited the ground fault could be replaced, utility power was lost and a filter fault occurred due to a voltage spike. This took the system out of operation temporarily. Although the ground-faulted cell was replaced and the system placed back "on line" in a standby mode, some additional cells showing high-resistance ground faults also had to be replaced before implementation of the modified load peak-shaving scenario for a full billing month. The BESS system was down for a good portion of the month of August 1996 while this and other maintenance was carried out on the battery and inverter. Seventeen individual cells that were questionable due to either a potential ground fault or low voltage at the end of the periodic discharges were replaced. The torque of all of the intercell connections in the battery was checked at the same time, and GE personnel visited the site to perform routine inspections of the inverter equipment while the system was off-line.

The BESS was restarted on September 10, 1996, using the modified load peak-shaving scenario described earlier, which provides power when plant demand is in



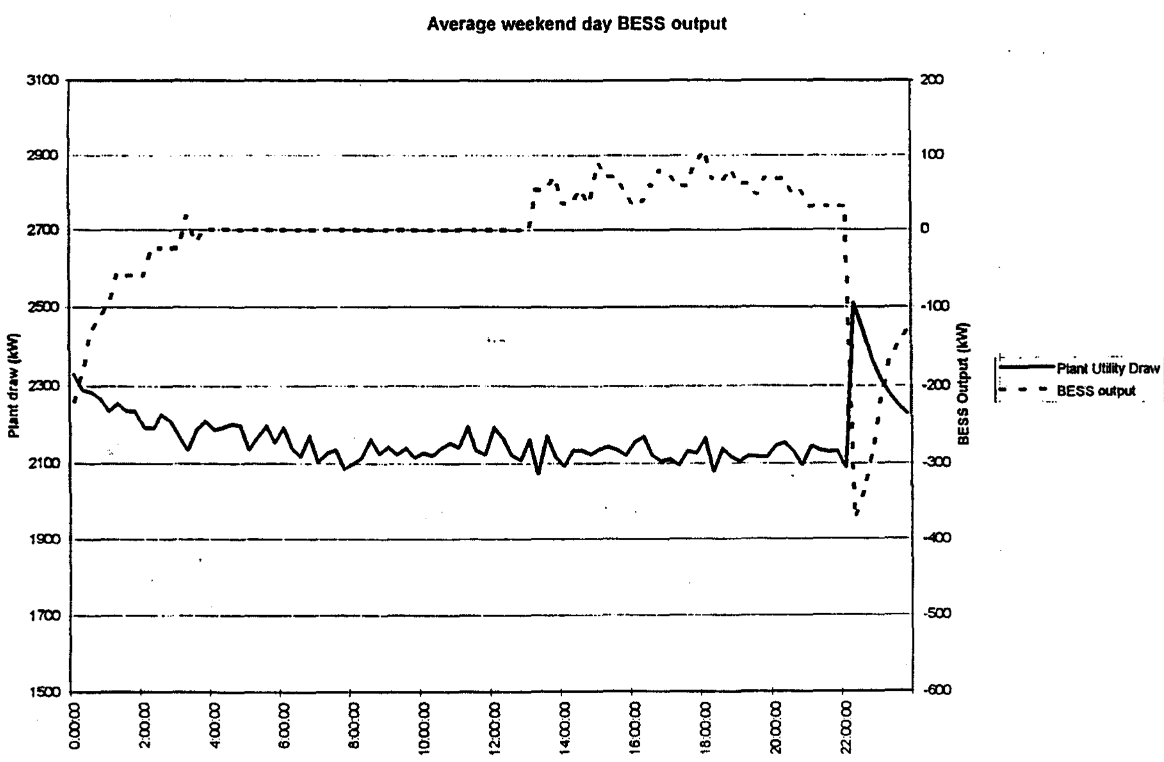


Figure 5-9. Plant and BESS Operation for a Typical Weekday and Weekend Day during a Block-Loading Test.

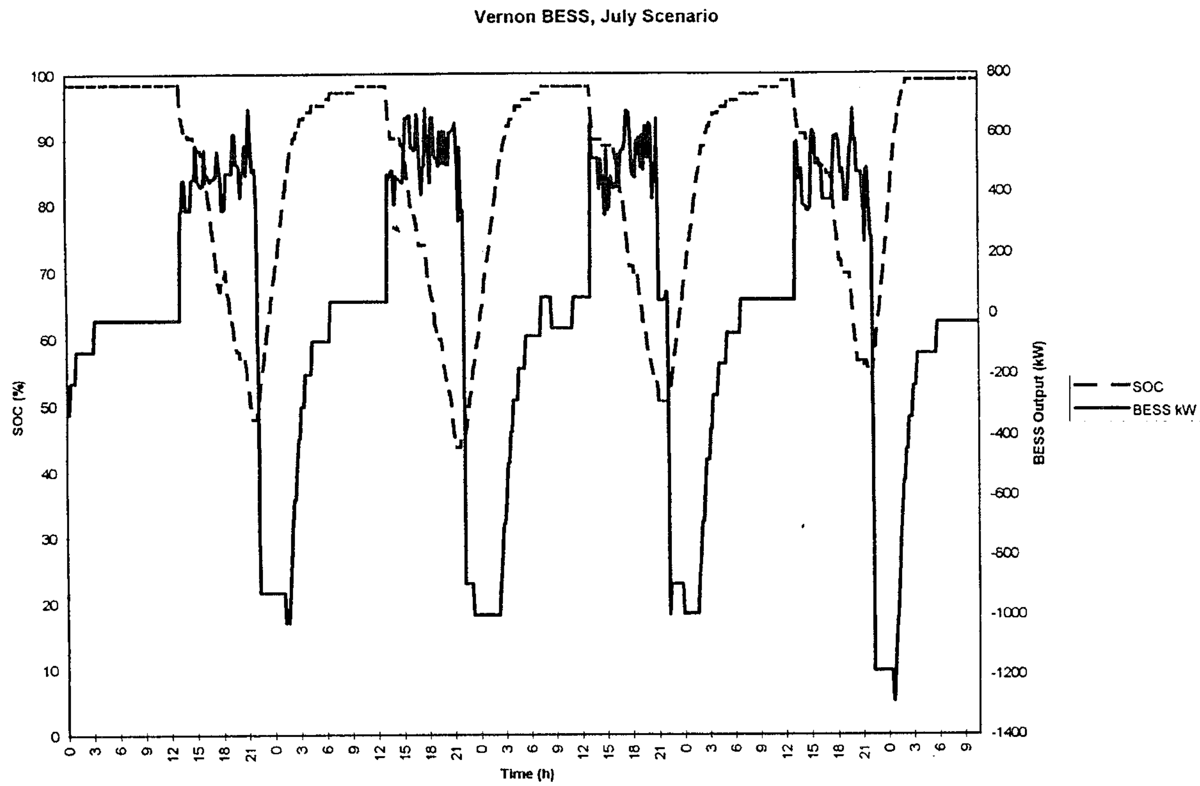


Figure 5-10. Four Daily BESS Cycles in July Using the Modified Load Peak-Shaving Profile.

excess of 2900 kW. This operational scenario was run for the balance of September and was scheduled to continue throughout the month of October in order to coincide with the City of Vernon's billing cycle. A chart showing the operation of the BESS for the period September 16-30, 1996, is shown in Figure 5-11. The BESS provided approximately 500 kW of the plant's load during each weekday and about 300 kW on weekends. The nominal plant load was 3300 kW. Battery SOC ranged between 100 and 50%, and the system had just enough time to recharge overnight before being discharged again.

During September, the BESS experienced two unusual incidents: (1) The City of Vernon's utility power failed at about 4 a.m. on September 3, 1996, for approximately 1 min. The BESS picked up the plant load as designed. (2) The BESS tripped off-line due to a PCP (inverter) fault on September 16, 1996. The inverter was reset and the system resumed its operational profile. No explanation has been found for the PCP fault.

The BESS facility was visited by several tour groups made up of attendees at the IEEE T&D Show that was held in Los Angeles in September 1996. Two open tours for general attendees at the show were conducted on September 17 and 19. A total of 36 people, most of them from utility companies, were in these general tour groups. Private tours were also conducted for representatives from HELCO, Golden Valley, Power Engineering, and GE's Field Engineering Service Group. Follow-up with all visitors to the BESS site will be pursued.

PV/Hybrid Evaluation Project

The evaluation of the Omnion PV/Battery hybrid controller at SNL's PV Test Facility was successfully completed in FY95. Present plans call for the installation of the prototype control unit in an industry facility in combination with a PV array. A multiyear operational test is planned. For the no-cost loan of the controller, data on performance, reliability, and maintenance will be provided to SNL for analysis and publication. Negotiations are in progress to formalize this task.

Status

Following a year-long search for an appropriate utility test site for the Hybrid Power Processor and Control System (HPPCS), the Arizona Public Service Com-

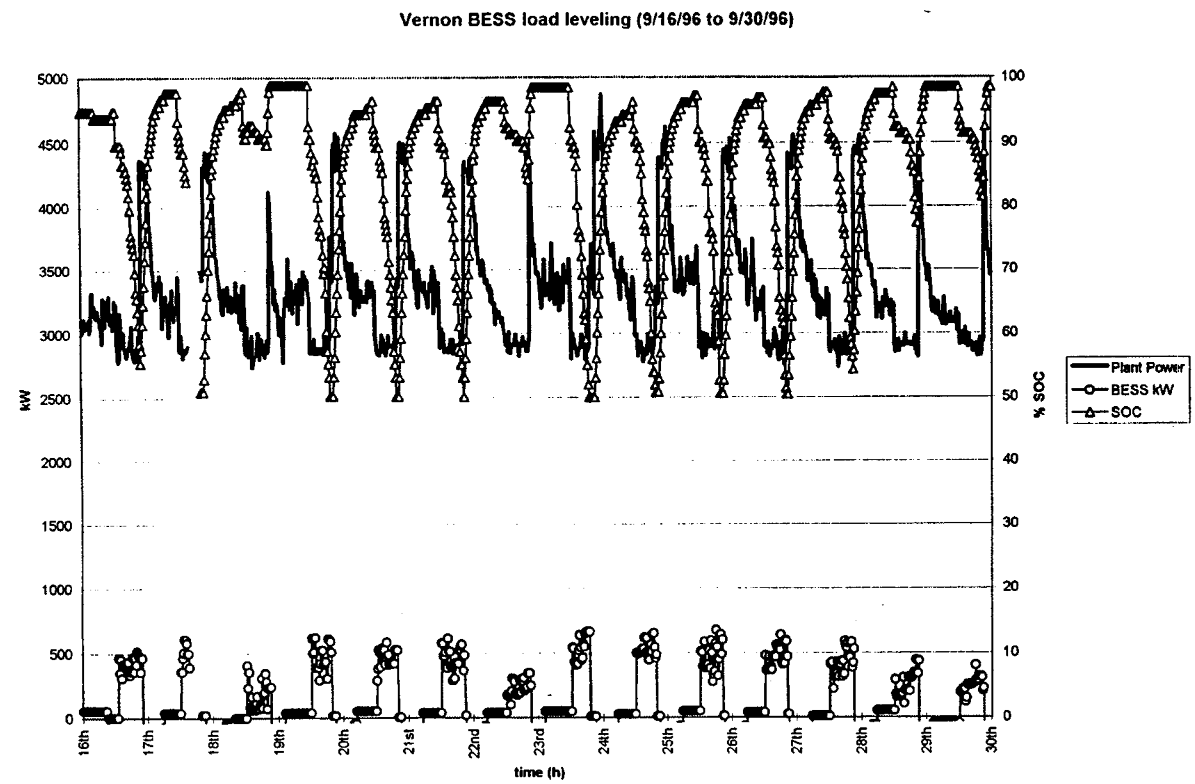


Figure 5-11. Operation of the BESS during the Second Half of September Using the Modified Load Peak-Shaving Scenario.

pany (APS) agreed late in the fourth quarter of FY96 to sponsor a 1- to 3-yr test program for the HPPCS. The HPPCS was developed by Omnion Power Engineering Corporation under a program sponsored jointly by SNL's Battery Analysis and Evaluation Department and PV System Applications Department. Figure 5-12 shows the closed cabinet for the HPPCS that will be tested at APS. Also included in the APS field test program will be the evaluation of a fuzzy-logic-based ACU developed by Raydec under a contract administered by the PV System Applications Department.

The HPPCS was specifically designed to operate under the control of an external intelligent battery controller such as the Raydec ACU. The HPPCS and ACU are designed to operate in a fully automated environment requiring no operator intervention to perform all system functions. The following functions are just a few of the system's automated capabilities:

- Can determine the most efficient power source available and activate the source.
- Can provide for the seamless transfer of loads to a selected power source.
- Can determine when battery charging or equalization is needed.
- Can provide supplemental power from storage when adequate power is not available from the genset.

Figure 5-13 shows the internal layout of the control and power processor electronics for the HPPCS.

Under the tentative terms of a draft APS Memorandum of Understanding (MOU) with SNL and the DOE, APS has agreed to build and operate a test facility to house the HPPCS and ACU units at the APS Solar Test and Research (STAR) Center in Tempe, Arizona. APS also agreed to acquire a large battery on the order of 200 kWh to support the test effort and to supply a 30-kW genset and a 15-kW PV array to complete the hardware complement required to operate a typical hybrid system. The hybrid system is designed to provide all the power necessary to operate the STAR facility throughout the test period. In addition, the complete hybrid system will be fully instrumented with a comprehensive data acquisition system provided under an SNL PV System Applications Department contract with the Southwest Technology Development Institute, which is operated by NMSU.

Final approval of the APS/DOE/SNL MOU is expected in the second quarter of FY97. The system should be fully integrated, tested, and activated at the APS STAR Center during the third quarter of FY97.

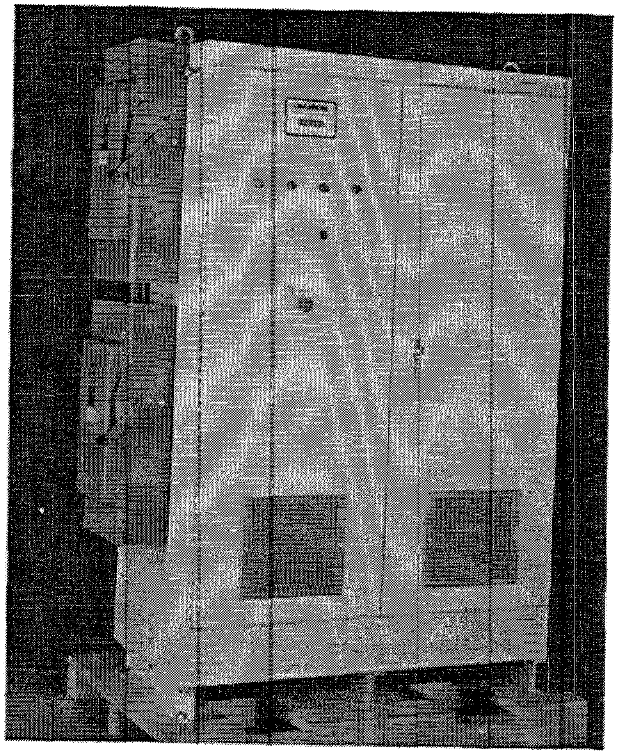


Figure 5-12. Closed Cabinet for the HPPCS showing the Junction Boxes for DC Input Sources for the System.

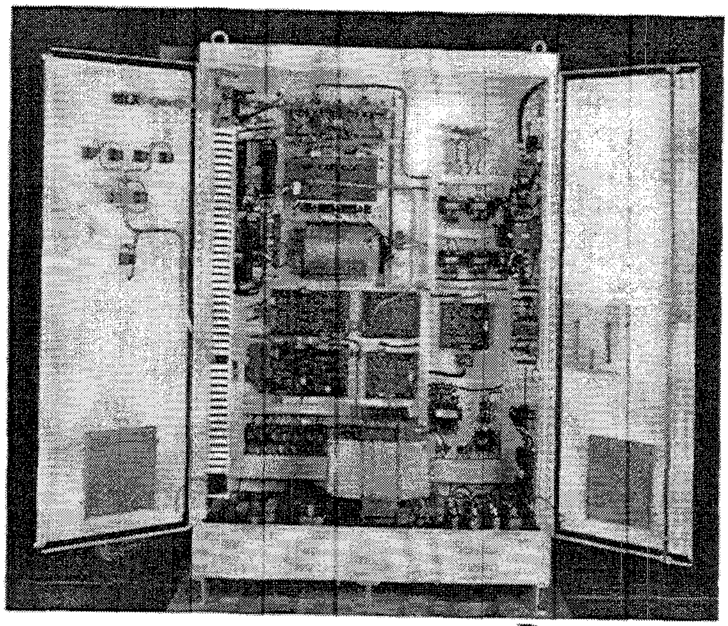


Figure 5-13. HPPCS Control and Power Electronics Layout.

6. Information Exchange

Introduction

Work in the Information Exchange element concentrates on focused communication to promote interest in energy storage and to provide forums in which ideas are shared, information is exchanged, and cooperative projects are initiated.

UBG/ESA Support

Status

The eleventh (and last) meeting of the UBG was held on May 15-16, 1996, following a two-day Steering Committee meeting at City of Industry, California. A series of decisions marked a major turning point in the evolution of this utility/industry group. First, the group was incorporated and Jon Hurwitch, Switch Technologies, was selected as the Executive Director. Mr. Hurwitch will assume the operational responsibilities of the group's affairs. Second, the general membership voted to adopt fundamental changes in both the mission and name of the UBG. The group voted to change its name from the UBG to the ESA and to amend the charter to expand the organization's scope and mission to encompass not only batteries but also other storage technologies. The meeting included tours both of the new battery system installed by GNB at the Vernon battery recycling plant and of the Southern California Edison (SCE) Chino battery. Registered members of the UBG also obtained a copy of the UBG Index, a software database of more than 800 organizations and individuals interested in batteries and energy storage.

The changes adopted by the former UBG at this meeting are aligned with the ESS program objectives of guiding the group towards self-sufficiency and eliminating its reliance on DOE support. The changes implemented during this meeting signal a transition towards that end. These changes will also modify the way in which the ESS Program interacts with the group in the future. With a highly reduced reliance on funding support from the ESS Program, the relationship between the UBG and the ESS that existed until this point will change. The ESS participated first as an advisor in the initial conception and formation of the UBG, contributing to the writing of its charter and the bylaws governing its early operation. Next, the ESS staff served in a non-voting, advisory capacity to the Steering Committee. In this role, the ESS Program played an important role in defining the purpose, identity, and direction of the group, even though it acted strictly in an advisory capacity. The overall goal of ESS participation in this process was to ensure that the group would eventually grow into a strong, industry-supported advocacy group with little or no reliance on DOE support for its ongoing operations. The steps taken during this meeting show that the organization has largely met that goal. Now the role of the ESS and its purpose for participating in the new ESA will be to (1) seek industry partnerships to achieve programmatic goals, (2) use the ESA channels for industry outreach, and (3) create a storage technology assistance center under the ESA umbrella.

Another highlight of the eleventh meeting was a tour of the recently completed 3.5-MWh GNB Battery System at GNB's battery recycling center in Vernon. In addition to providing backup to critical air handling equipment, this battery system can reduce the plant's peak demand by as much as 500 kW. The battery system is the first implementation of the design that evolved from the GNB alliance with GE. The Vernon project was primarily internally funded by GNB to demonstrate GNB's ABSOLYTE technology and showcase this type of storage application. Approximately 10% of the cells at the Vernon battery facility were provided under ESS Program funding as a field test. GNB intends to use the system as a marketing tool for the standardized battery system design, which uses GNB batteries and inverters/controls supplied by GE. Figure 6-1 is a view of the battery room looking through the PCS room.

The first meeting of the ESA is scheduled for early November near Oglethorpe Power Corporation's PQ2000 demonstration site in the vicinity of Jacksonville, Florida.

Executive Briefings

In response to changes in the electricity industry, the DOE has redirected the ESS Program focus from purely battery-based energy storage systems to systems that employ one or more of the following storage technologies: batteries (lead-acid and advanced), flywheels, superconducting magnets, and supercapacitors. To ensure that the direction of the program was responsive

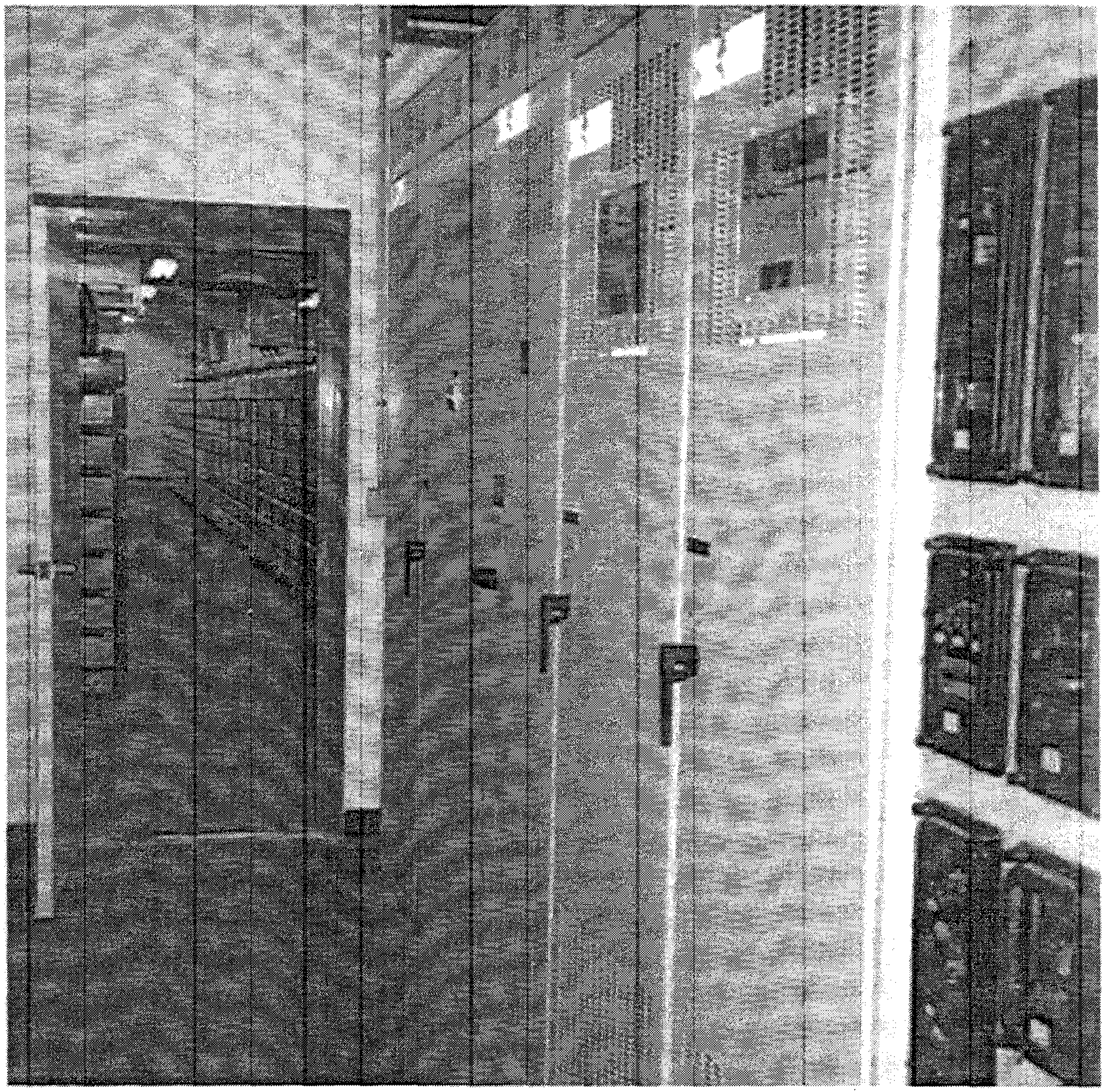


Figure 6-1. View of the GNB Battery from the PCS Room.

to the changing needs of the nation's electricity industry, the DOE sponsored a series of meetings with industry executives in which ESS Program management solicited input regarding expected changes in the utility industry and the long-term R&D that would be most appropriate for the emerging business environment.

The Executive Meeting Project had three goals: (1) to communicate to industry the scope and rationale of ESS Program activities relative to DOE understanding of the electric utility industry, (2) to solicit energy stakeholders' perspectives on the changes in the electric utility industry and the likely federal R&D needs that will stem from those changes, and (3) to recruit ongoing industry participation in an Industry Users Group that helps the Program remain focused on the activities that meet the nation's energy needs.

The information exchange was expected (1) to broaden the ESS Program focus from that of a BES program to one that includes a portfolio of energy storage technologies and (2) to provide a better understanding by both the DOE and industry of each others' requirements and to identify well-defined areas and mechanisms through which the DOE and industry could collaborate on specific development and deployment projects.

Status

Program representatives contacted selected organizations to arrange a 2-hr meeting of the DOE Program team (the DOE ESS Program Manager, the ESS Program Manager at SNL, and an industry expert) as well as representatives from diverse divisions of the organization visited. The ESS Program met with organizations around the U.S. between March and September 1996. The attendance at the meetings ranged from 5 to 30 persons. Each of the meetings contributed to the overall goals of the project. Table 6-1 lists the organizations visited.

The Executive Meetings Project has provided numerous benefits to the ESS Program and to industry by providing an opportunity for industry involvement in energy storage technology development and demonstration. These benefits, summarized below, represent accomplishment of the goals and objectives that were identified for the industry outreach project.

1. Increased industry awareness of the ESS Program, especially on the part of several organizations visited that were not then involved in the ESS Program. Even the organizations visited that were previously involved in the ESS program learned more about ESS Program activities because senior business and technical managers who were not directly involved in the company's storage activities were informed. By spreading awareness to the senior level, there is a potential for greater institutional support of the program as well.

2. Increased the DOE's awareness of industry's interests and needs relative to the ESS Program's activities. Insights were gained into the interests and needs of different industry sectors through one-on-one meetings. These insights were analyzed and are being incorporated into ESS Program planning.

3. Identified areas of mutual technology interest. Some participants identified distinctive capabilities that could be applied to the ESS Programs research efforts.

The informal meeting format encouraged the industry participants to do most of the talking and permitted open and unencumbered discussions. The DOE benefited from the executive meetings and will benefit from

Table 6-1. Utility Executive Meetings with DOE Program Team

Organization Visited	Type of Organization	Date of Meeting
AES, Arlington, VA	IPP	September 1996
Central & Southwest, Tulsa, OK	IOU	August 1996
Indiana Power & Light Co. (IPALCO), Indianapolis, IN	IOU	May 1996
Northern States Power (NSP), Minneapolis, MN	IOU	April 1996
Potomac Electric Power Co. (PEPCO), Alexandria, VA	IOU	April 1996
PNM, Albuquerque, NM	IOU	August 1996
SCE, Los Angeles, CA	IOU	May 1996
The Southern Company, Atlanta, GA	IOU	September 1996
Allegheny Power, Harrisburg, PA	Co-op	August 1996
NRECA, Arlington, VA	Co-op	September 1996
Oglethorpe, Atlanta, GA	Co-op	September 1996
Salt River Project (SRP), Phoenix, AZ	Co-op	August 1996
GNB, Chicago, IL	Manufacturer	May 1996
Kennetech, San Francisco, CA	Manufacturer/IPP	May 1996
SI, Madison, WI	Manufacturer	March 1996

the Industry Users Group as well. Industry gained insight into the program and access to research that could lead to a competitive advantage in the marketplace as energy storage technologies emerge as commercial products. The dialogue that has been advanced by a project like the executive meetings is important for future cooperation between industry and the ESS Program, and crucial for developing the road map to define mutual objectives.

Trade Shows, Conferences, and Meetings

ESS Program staff attended and participated in various trade shows, conferences, and meetings. At the trade shows, the ESS Program booth is designed to encourage questions and discussion by highlighting the Program's history, achievements, and industrial partnerships. In addition, informal discussions are held, questions are answered, ESS literature is handed out, and requests for additional information are taken. During FY96, ESS Program staff attended two major utility trade shows and held a meeting at the California Energy Commission (CEC) offices.

DA/DSM '96 Conference, January 15-17, 1996

Members of the ESS Program staffed a display booth at the 1996 Distribution Automation/Demand-Side Management (DA/DSM) Conference in Tampa, Florida. This conference and exhibition, attended by more than 3200 people, was predominantly a forum for the exchange of information by people in the electric utility industry. The Program's emphasis at DA/DSM '96 was the success of the first fully commercial BES system installed at the Sabana Llana substation at PREPA. The immediate effect of the 20-MW BES system was to significantly reduce power interruptions to the manufacturing sector in the area served by this substation. The reduction in line stoppages has had a positive effect on Puerto Rico's productivity and competitiveness. PREPA continues to plan for an additional 80 MW of BES system capability. Requests for information on the PREPA project continue to be received by the ESS Program.

UPVG and Soltech Annual Meeting, March 12-15, 1996

The annual Utility Photovoltaic Group (UPVG) Meeting was combined with Soltech and held in Palm Springs, California, on March 12-15, 1996. The meeting was organized by the UPVG and the Solar Energy Industries Association. More than 550 members were preregistered. This was the first-ever conference bringing together representatives from both the electric utility industry and the solar energy companies to explore the challenges of their changing industries and the mutual benefits of cooperation. ESS Program staff set up an exhibit displaying posters summarizing the features of BES in renewable energy and utility applications. Discussions that were initiated at this conference with utility and solar engineers and consultants have continued.

Appendix: Presentations and Publications

Presentations

A.A. Akhil, "Utility Battery Storage Systems: Applications and Current Status," Presented to the Texas Public Utility Commission, Austin, TX, January 1996.

G.P. Corey and G.A. Buckingham, "A 2-MW, 10-Second Battery Solution for Short-Duration Power Quality Problems," Tenth International Power Quality Conference and Exhibition, Bremen, Germany, November 7-9, 1995.

G.P. Corey, "Battery Energy Storage Solutions for Premium Power," The Eleventh Annual Battery Conference on Applications and Advances, Long Beach, CA, January 9-12, 1996.

G.P. Corey and W.J. Nerbun, "A Utility Scale Battery Energy Storage Power Quality Solution," Power Quality Symposium, Sacramento, CA, April 4-5, 1996.

J.W. Stevens and G.P. Corey, "A Study of Lead-Acid Battery Efficiency Near Top-of-Charge and the Impact on PV System Design," 25th IEEE Photovoltaic Specialists Conference, Washington, DC, May 13-17, 1996.

Publications

P. Butler, P. Taylor, and W. Nerbun, Lead-Acid Batteries in Systems to Improve Power Quality, Fifth European Lead Battery Conference, Barcelona, Spain, October 2-4, 1996.

G.P. Corey, Energy Storage Solutions for Premium Power, in *IEEE Aerospace and Electronics Systems*, vol. 11, pp. 41-44, June 1996.

R.G. Jungst and M.D. Anderson, DYNASTORE Operating Cost Analysis of Energy Storage for a Midwest Utility. Sandia National Laboratories report SAND96-2238C. Proceedings of the Twenty Ninth Annual Frontiers of Power Conference, Stillwater, OK, October 28-29, 1996.

R.G. Jungst, M.D. Anderson, and J.T. Alt, Assessment of Utility Side Cost Savings from Battery Energy Storage. Sandia National Laboratories report SAND95-1545. Proceedings of the 1996 IEEE Power Engineering Society Winter Meeting, Baltimore, MD, January 21-26, 1996.

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